INTRODUCTION TO PARTICLE ACCELERATORS

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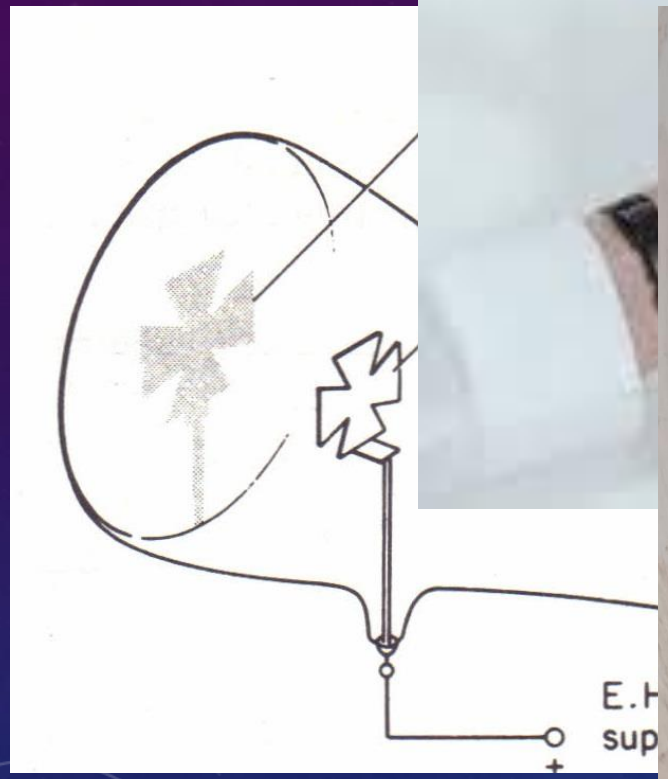
ACCELERATOR PHYSICIST

03/12/2025

WHAT IS A PARTICLE ACCELERATOR?



ACCORDING TO WIKIPEDIA:

A particle accelerator is a machine that uses electromagnetic fields to propel charged particles to very high speeds and energies to contain them in well-defined beams.

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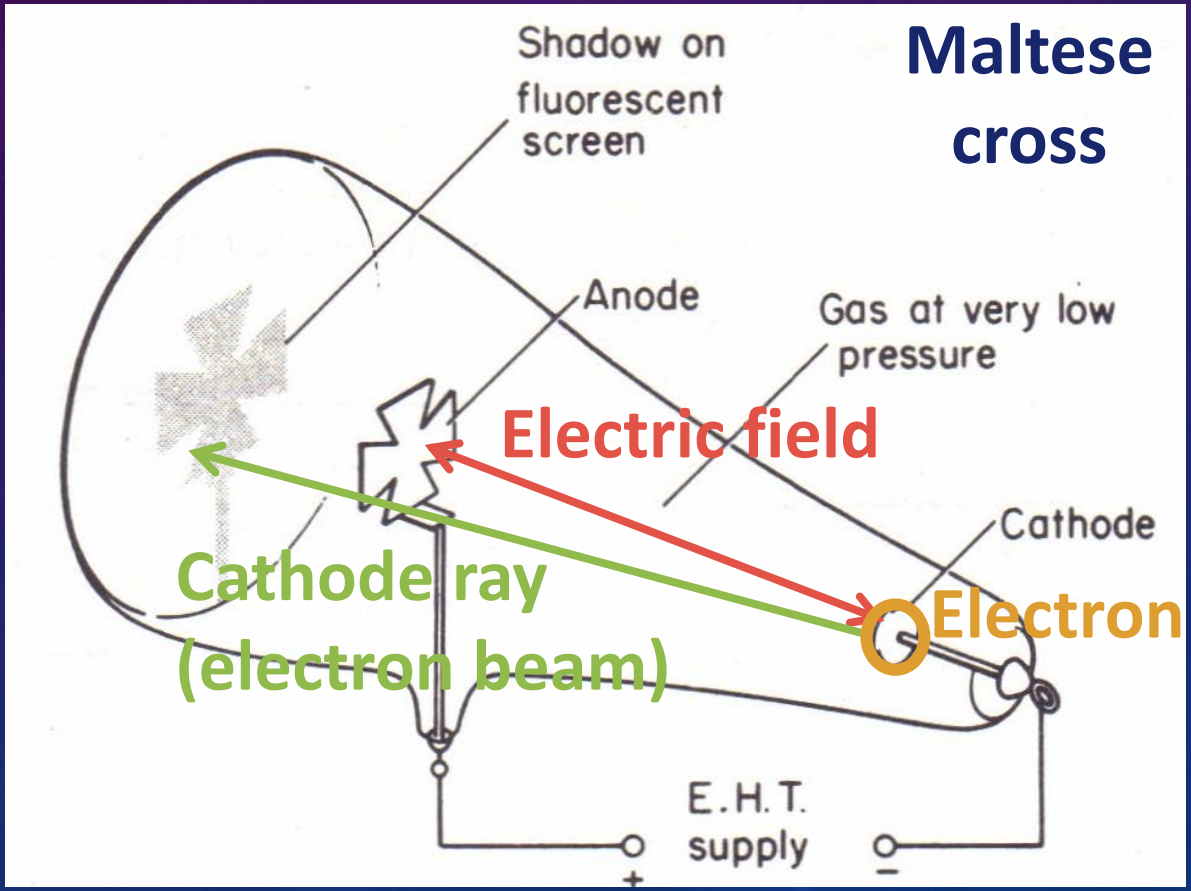

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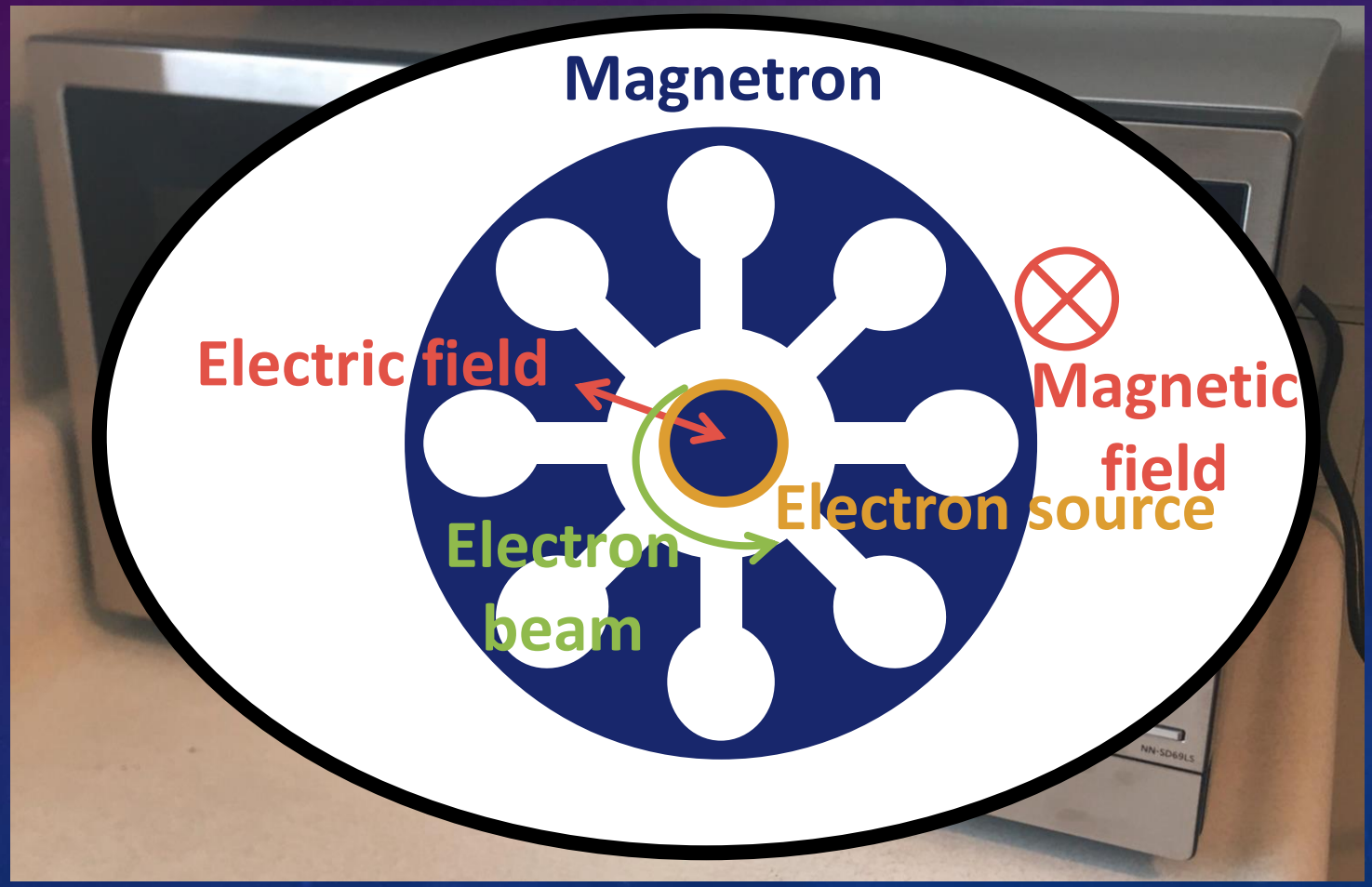

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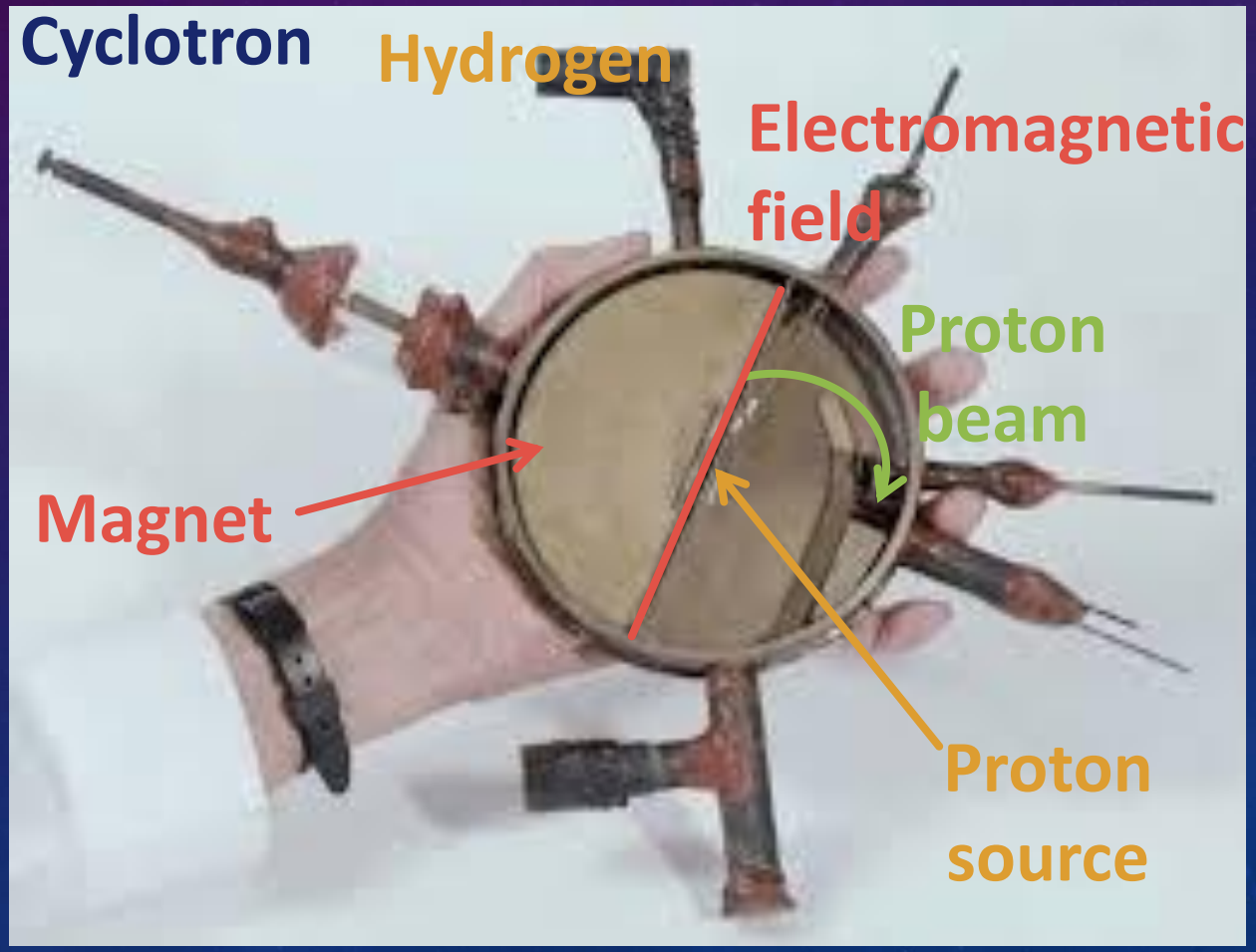

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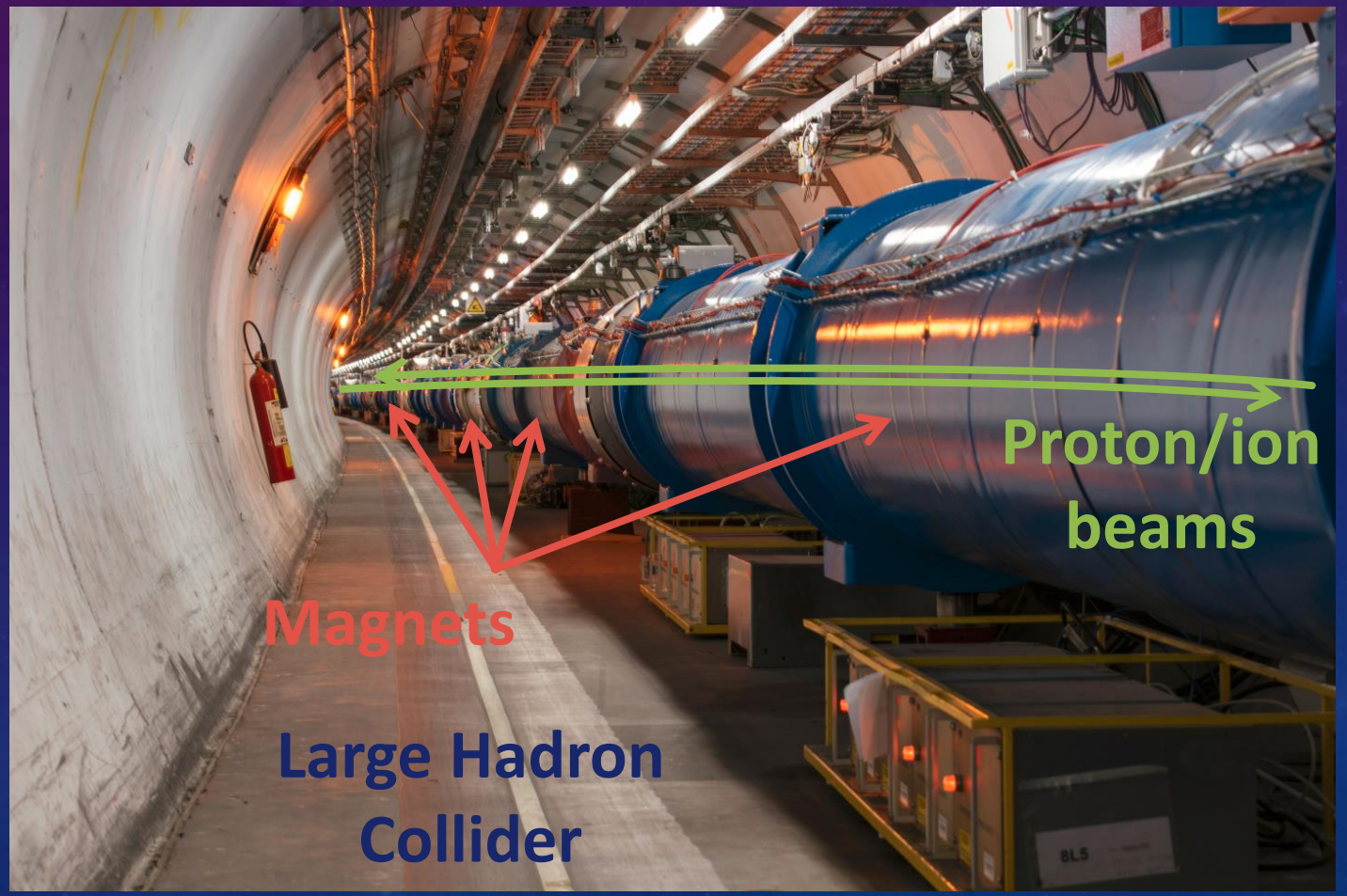
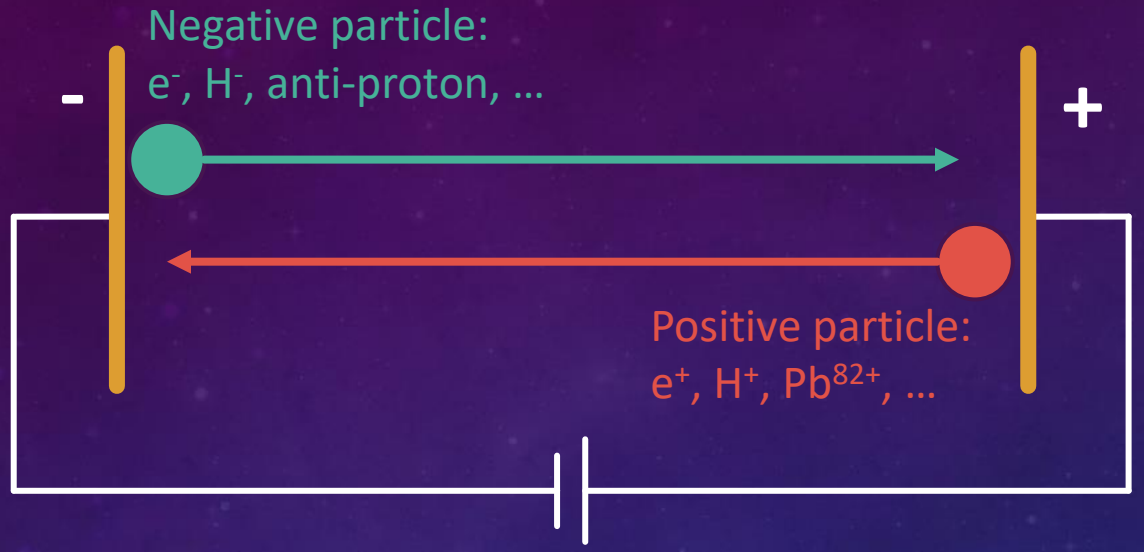


PARTICLE ACCELERATORS:

- Can be almost any size
- Use electromagnetic fields to manipulate beams of charged particles
- Range from household appliances to multi-national research facilities, and everything in between

ELECTROSTATIC ACCELERATION

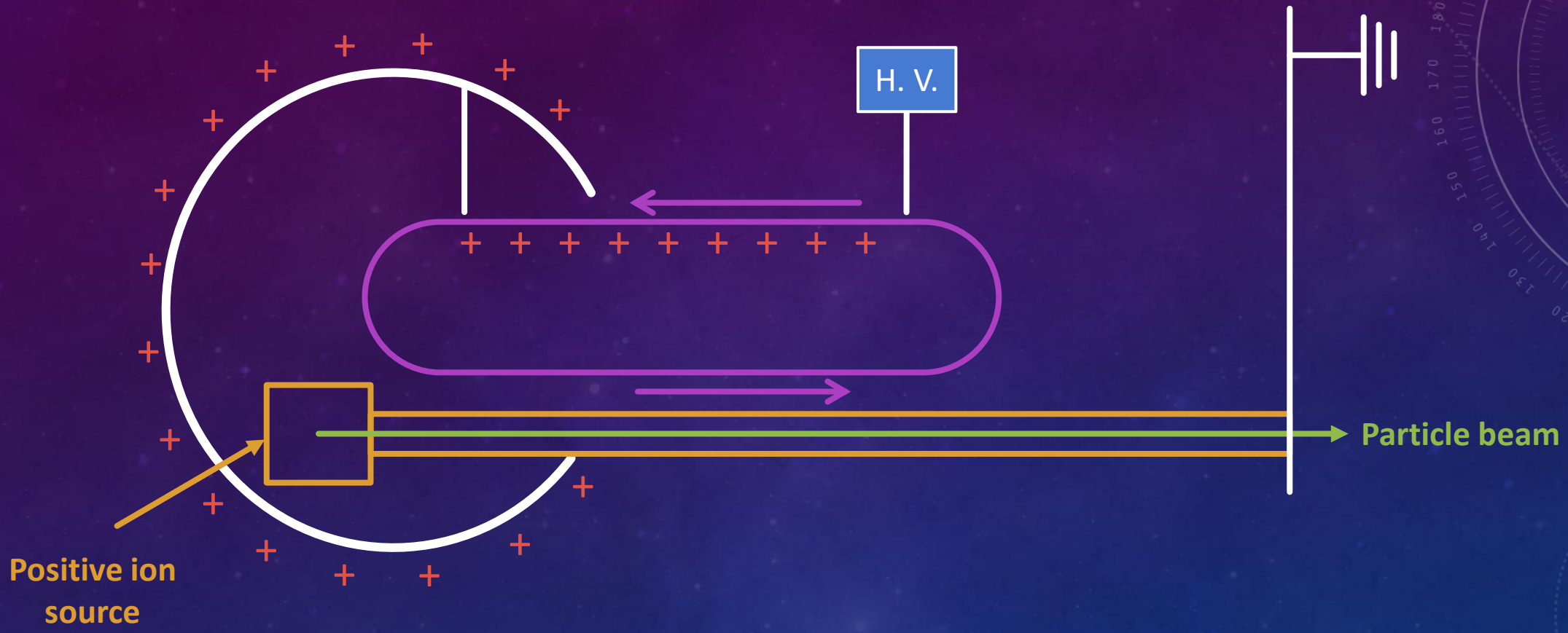


- A charged particle in an electric field will experience a force, and therefore accelerate
- An electron crossing a potential difference of 1 Volt gains 1 electron-Volt (eV) of energy (1.6×10^{-19} J)

$$\Delta E = qV$$

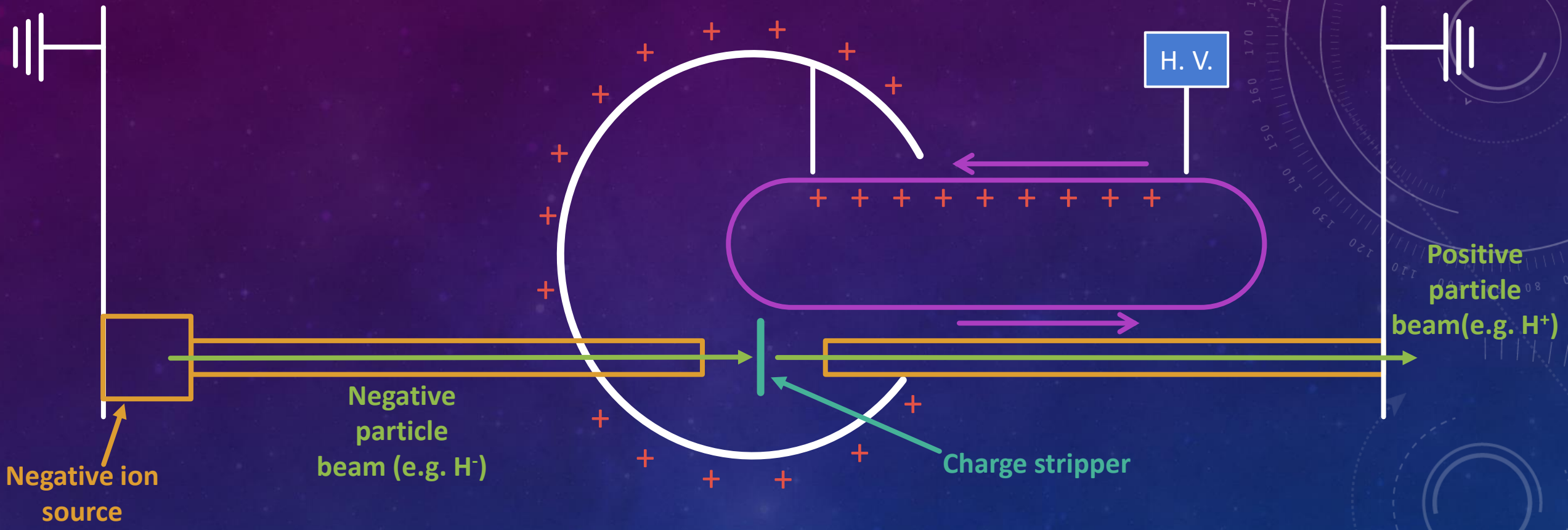
Change of energy = Charge × Potential difference

VAN DE GRAAF ACCELERATOR



- Ion source raised to Van de Graaf (VdG) potential
- Ions accelerated towards ground

TANDEM VAN DE GRAAF ACCELERATOR



- Negative ions accelerated from ground towards the VdG
- Excess electron(s) removed by a charge stripper
- Positive ions accelerated from VdG towards ground

THE LIMITS OF ELECTROSTATIC ACCELERATION

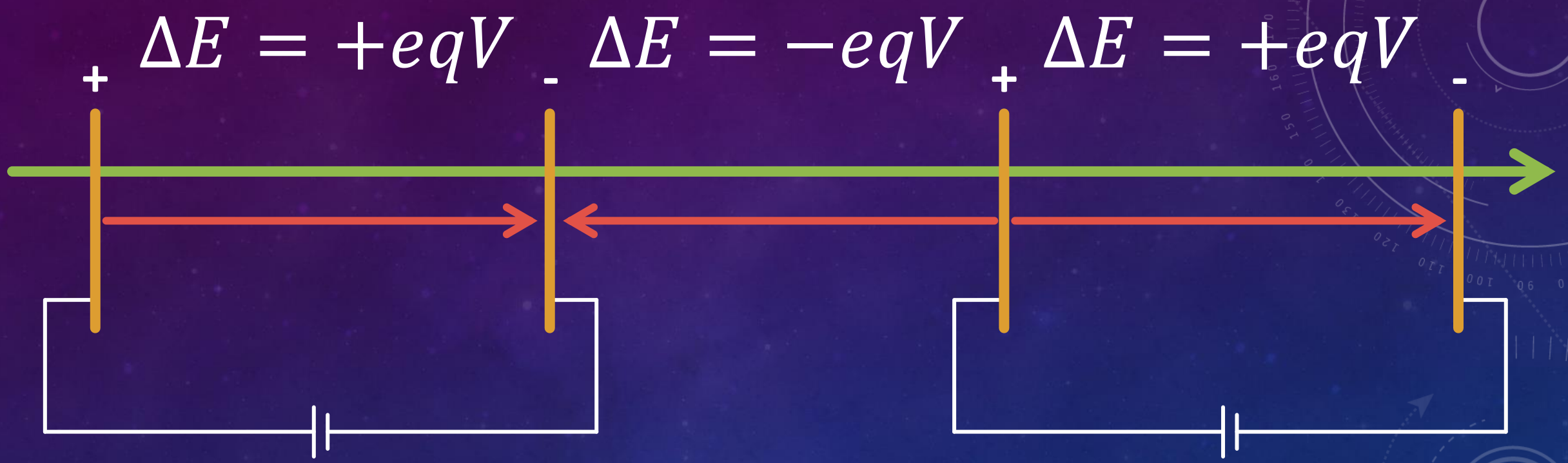
Western Michigan University:

Daresbury Laboratory: 20-30 MV

naven National Laboratory: 15 MV

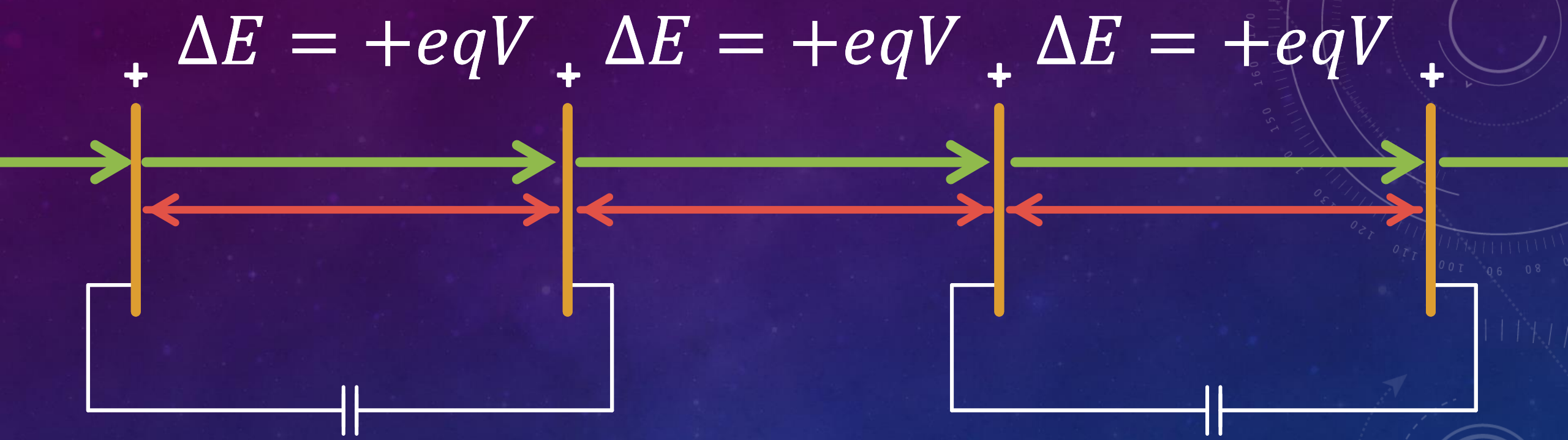
- Several methods to generate high electrostatic voltage exist (Van de Graaf, Cockroft-Walton, Pelletron, …)
- Limited by maximum field to the Mega-Volt scale, typically 10s – 100s kV
- Need Tera-Volts for the LHC

FROM DC TO AC



- Crossing multiple electrostatic gaps does not allow further acceleration
- Electric field points in the “wrong” direction between the gaps
- Need to change the direction of the electric field

FROM DC TO AC



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RADIOFREQUENCY ACCELERATION

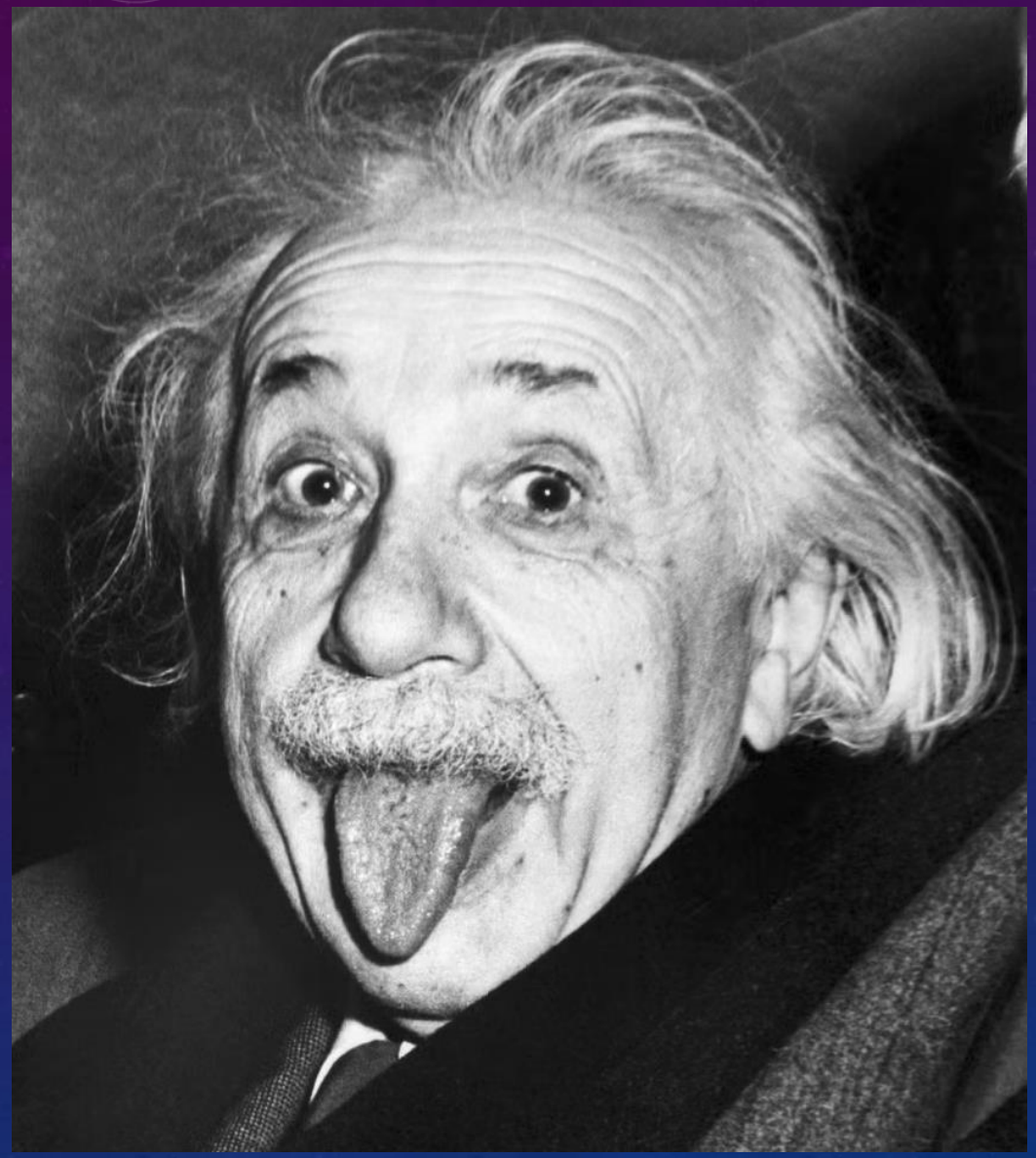
- Confine radio frequency (kHz – GHz) electromagnetic fields in a cavity
- Pass bunched beams through either a line of cavities or the same cavity multiple times
- Accumulate many small steps in energy, no need for extreme static fields

RADIOFREQUENCY ACCELERATION

- The voltage experienced depends on the phase (time) of arrival at the cavity
- Particles must cross at the phase that gives the correct voltage
- Requires precise synchronisation

$$\Delta E = qV\sin(\varphi)$$

Change of energy = Charge × Potential difference × Particle phase



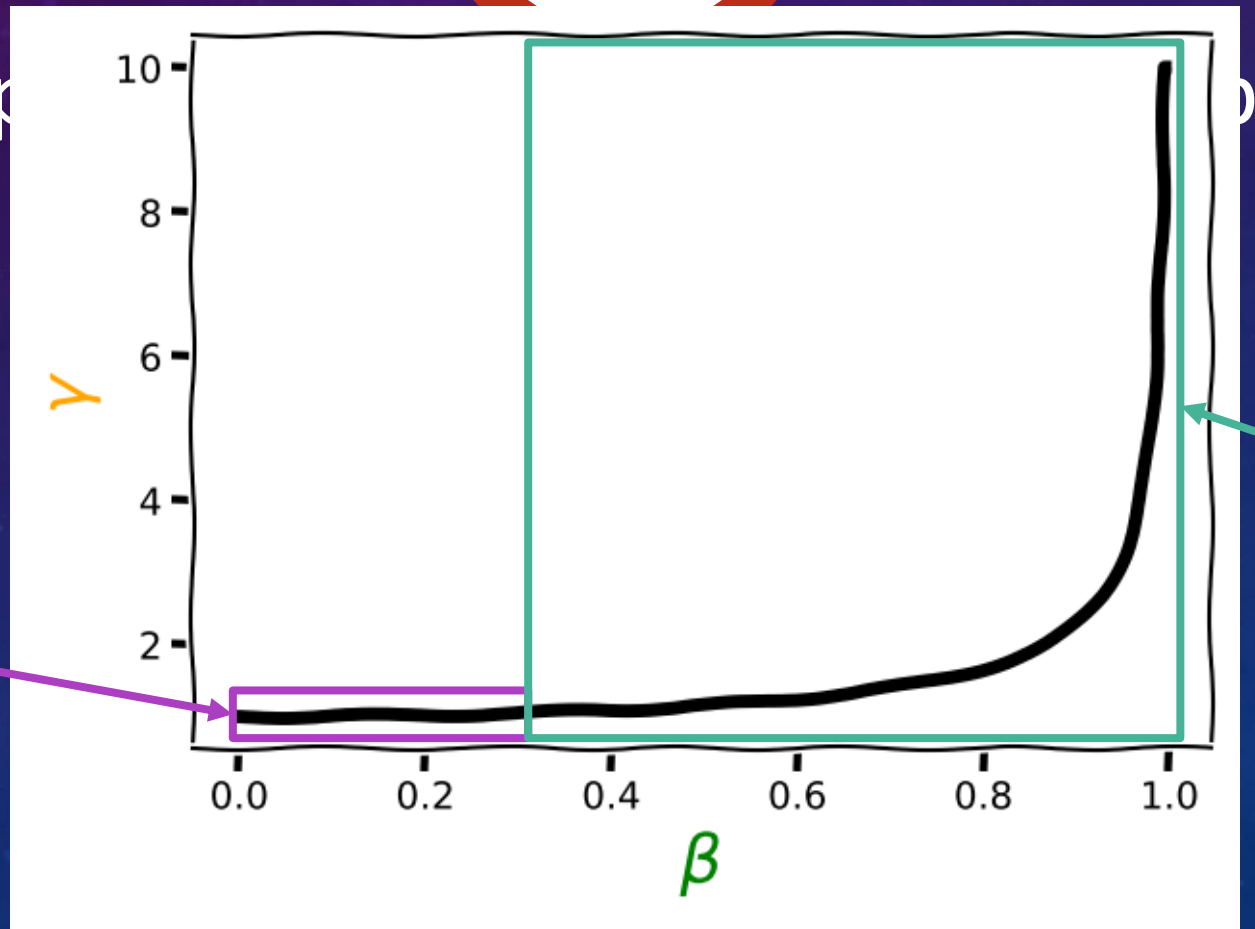
A LIGHT TOUR OF RELATIVITY

$$\beta = \frac{v}{c}$$

c

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

When this app roaches infinity



Newton

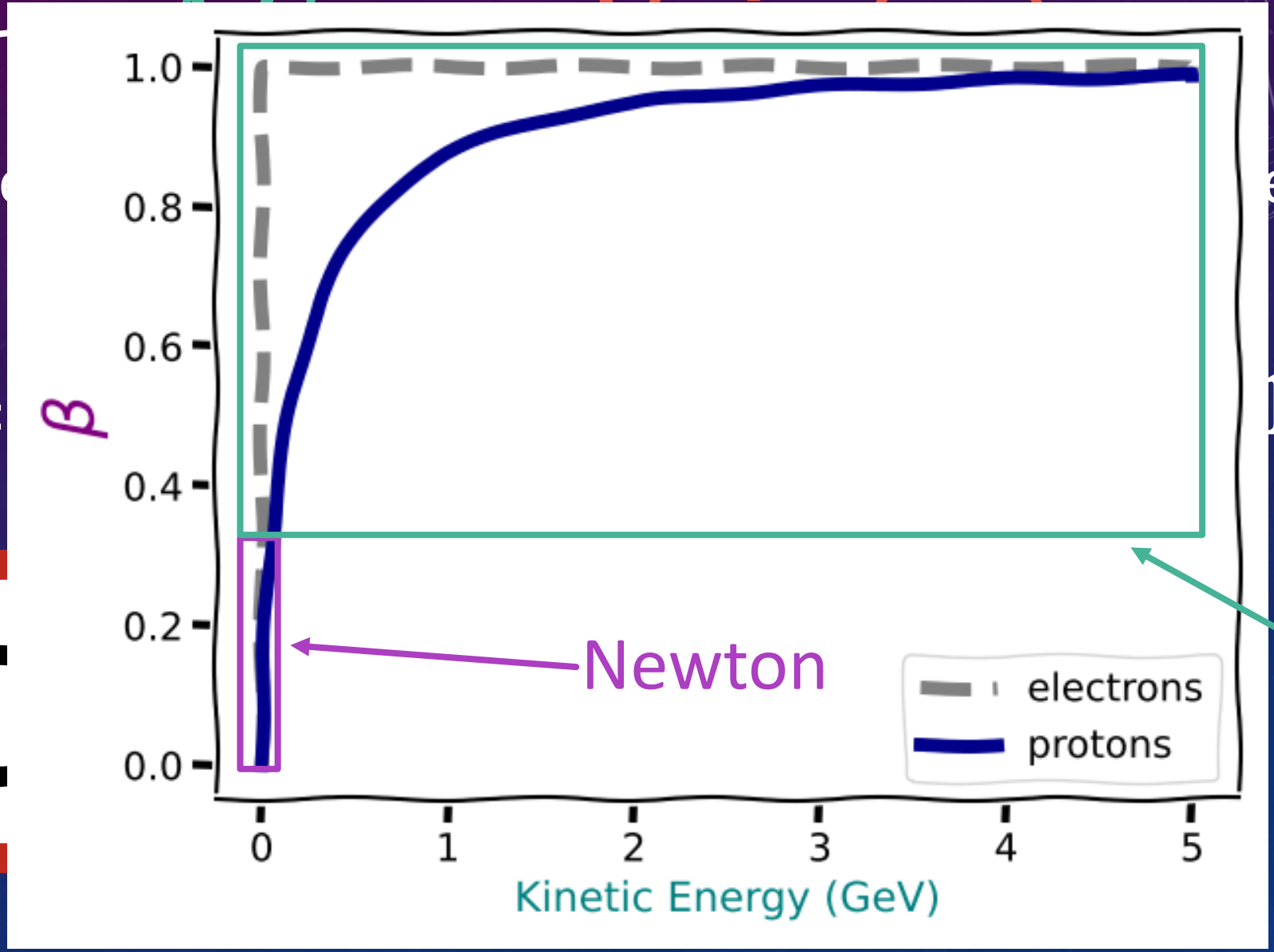
Einstein

IMPACT ON ACCELERATION AND ENERGY GAIN

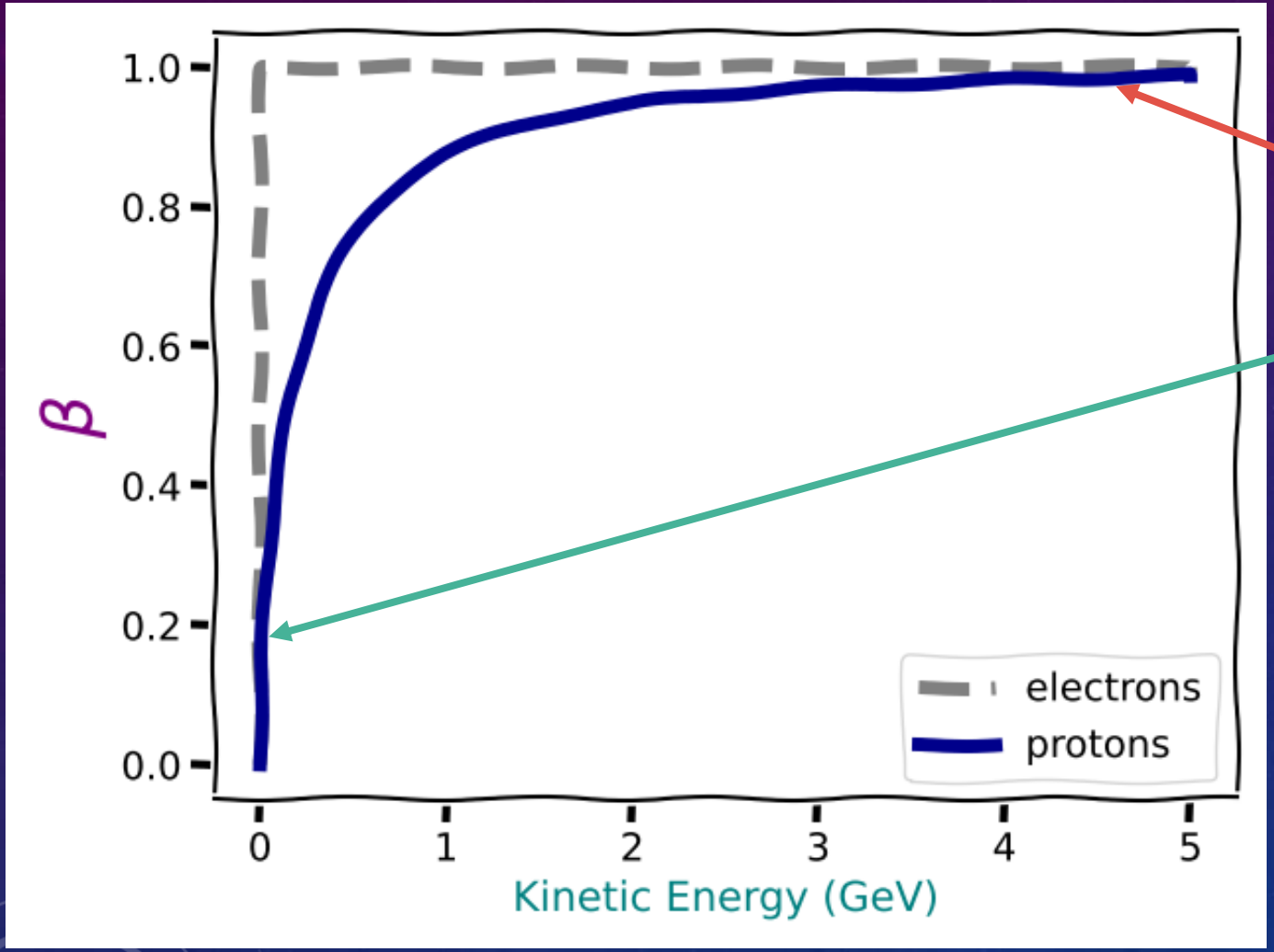
The

es

$$KE = \left(\frac{1}{\sqrt{1-\beta^2}} - 1\right) m_0 c^2$$

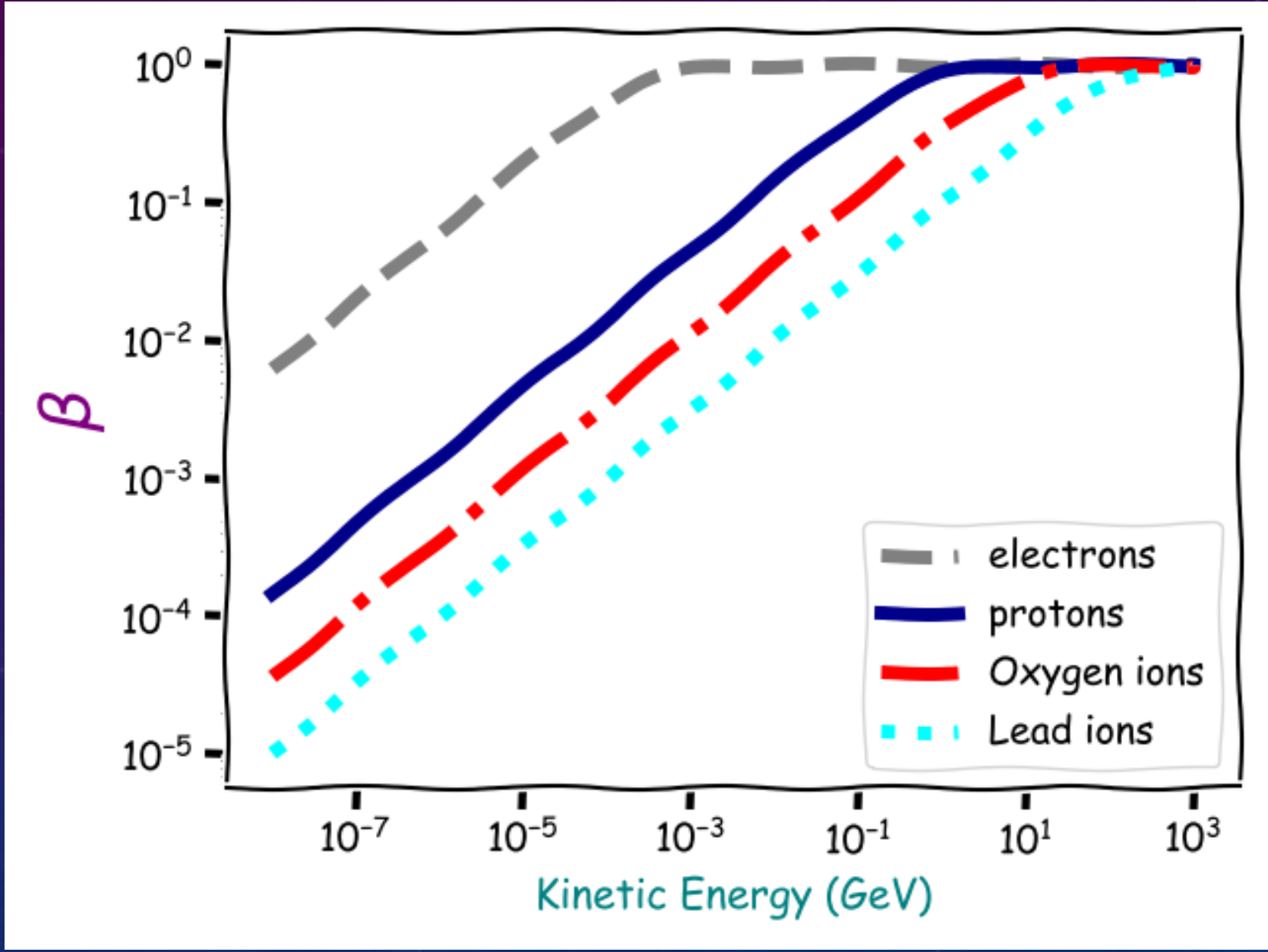


CHANGE OF SPEED VS CHANGE OF ENERGY



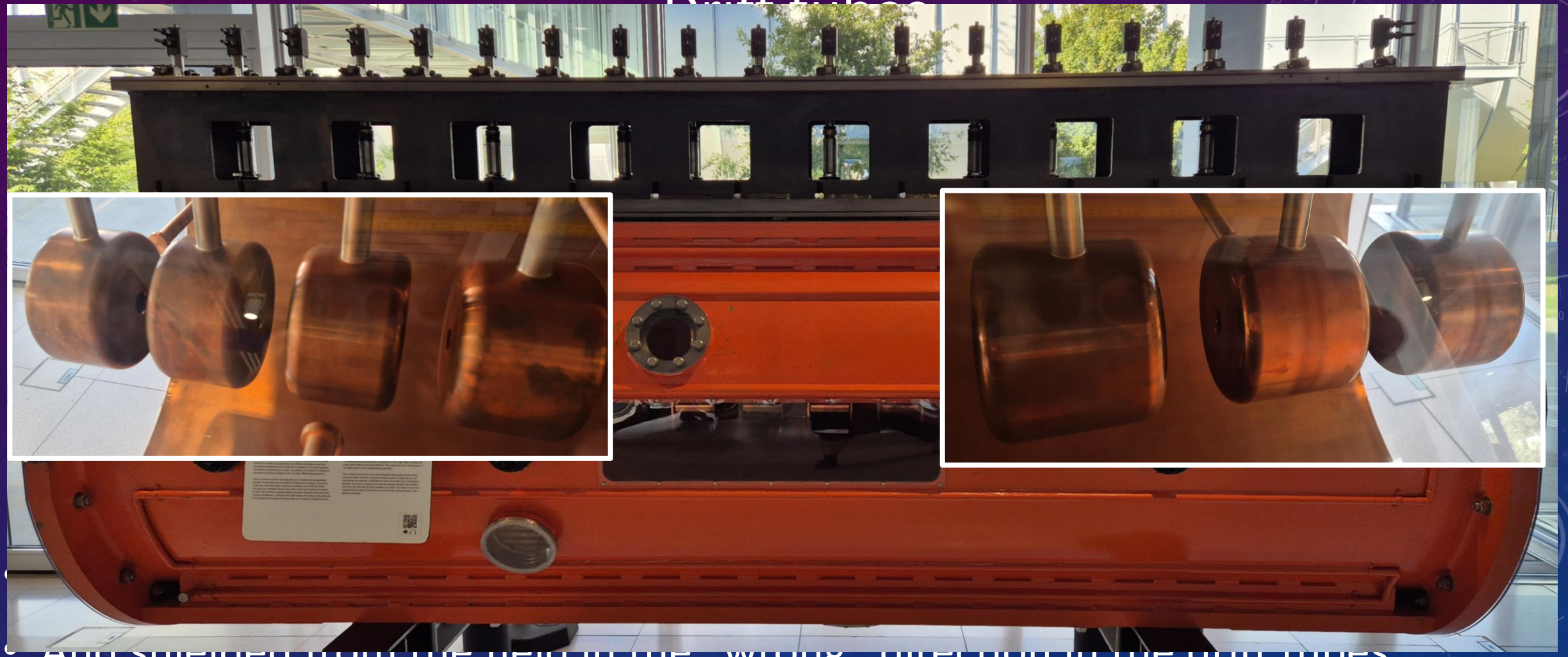
- At high energy, speed is almost constant
- At low energy, increased kinetic energy means increased speed
- Light particles (electrons) become relativistic very quickly
- Heavier particles (protons) require a lot more energy to become relativistic

CHANGE OF SPEED VS CHANGE OF ENERGY – INCREASING MASS



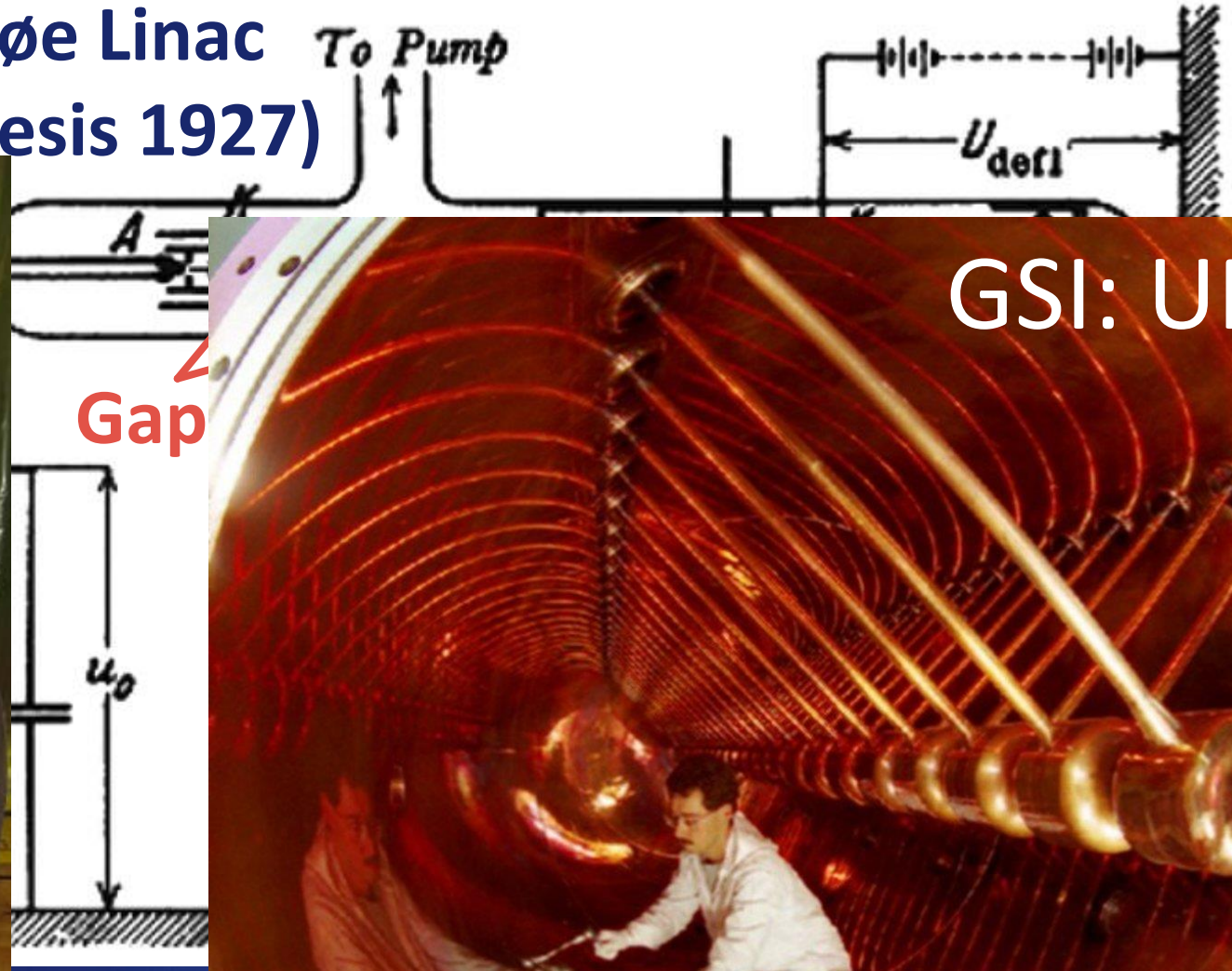
DRIFT TUBE LINAC

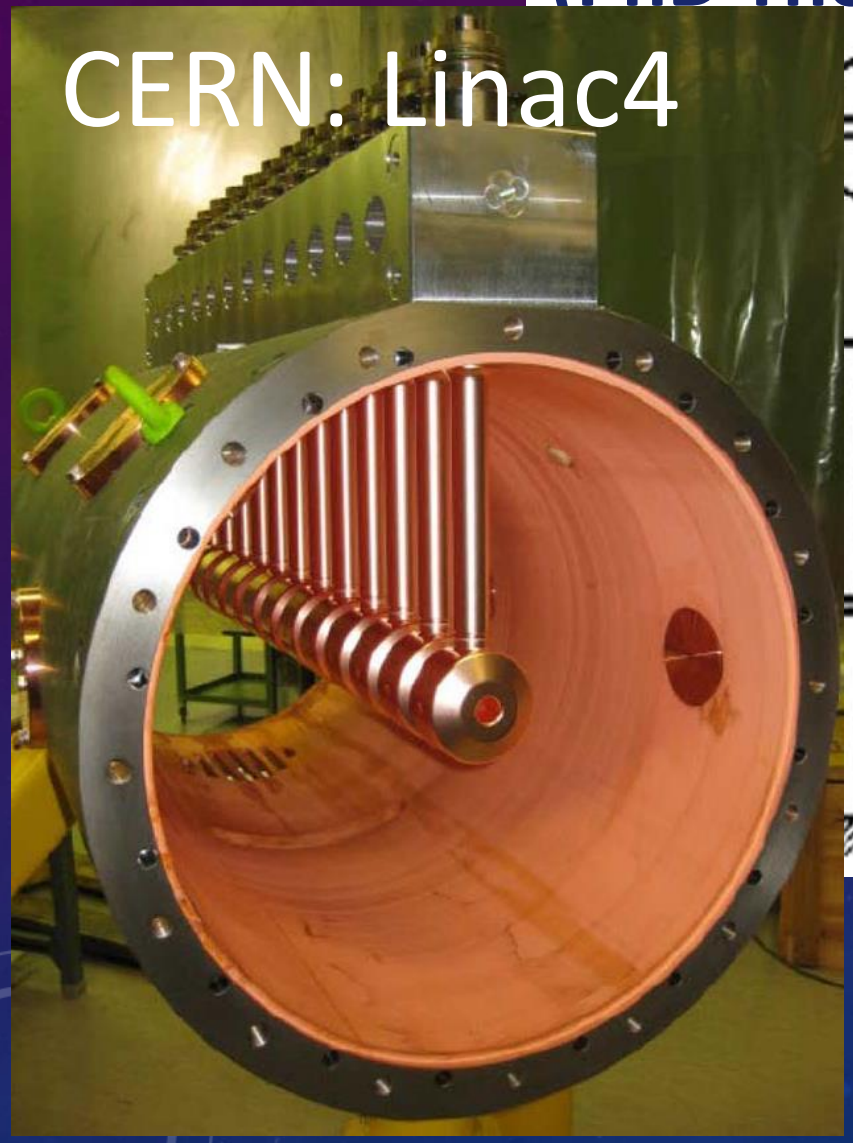
Drift tubes



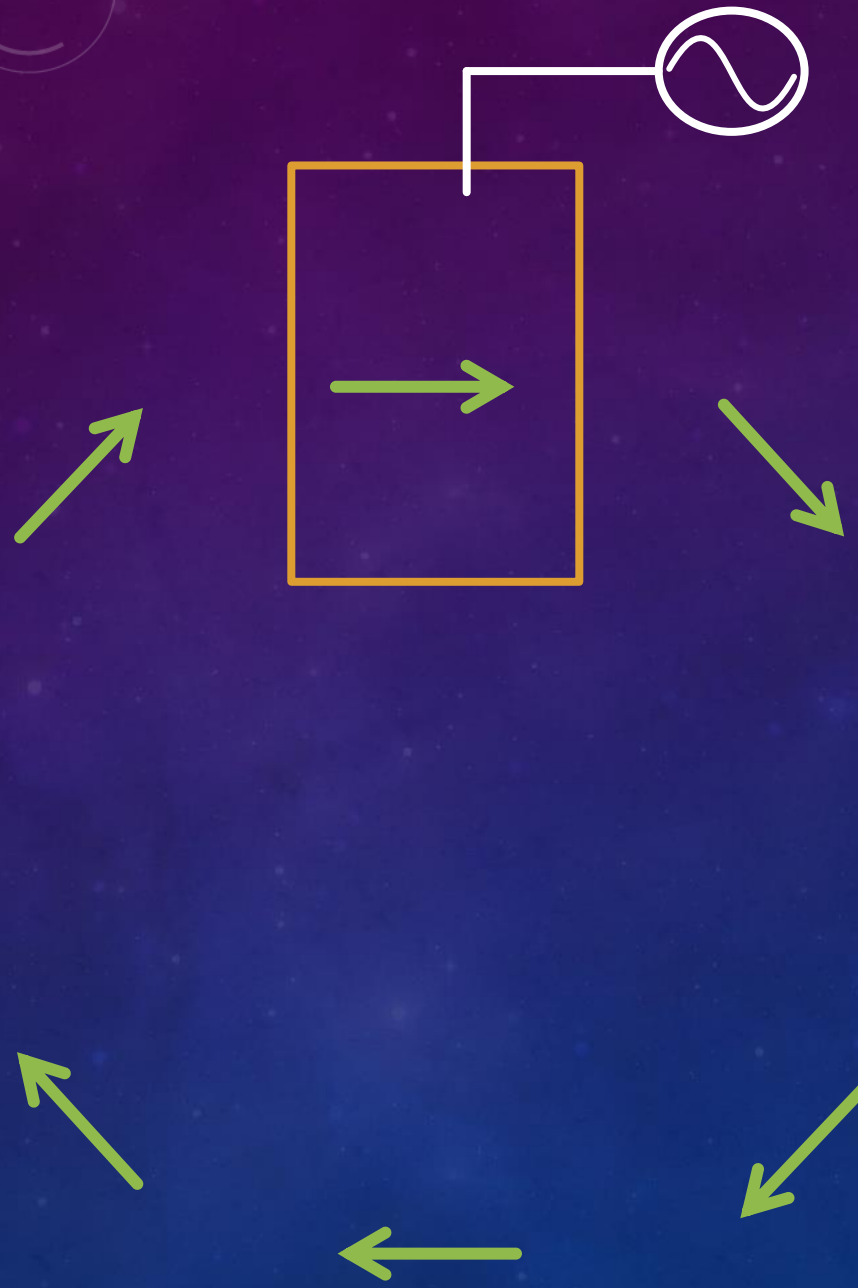
- And shielded from the field in the "wrong" direction in the drift tubes
- The drift tubes get longer because the particles get faster (low energy)

Widerøe Linac (PhD Thesis 1927)

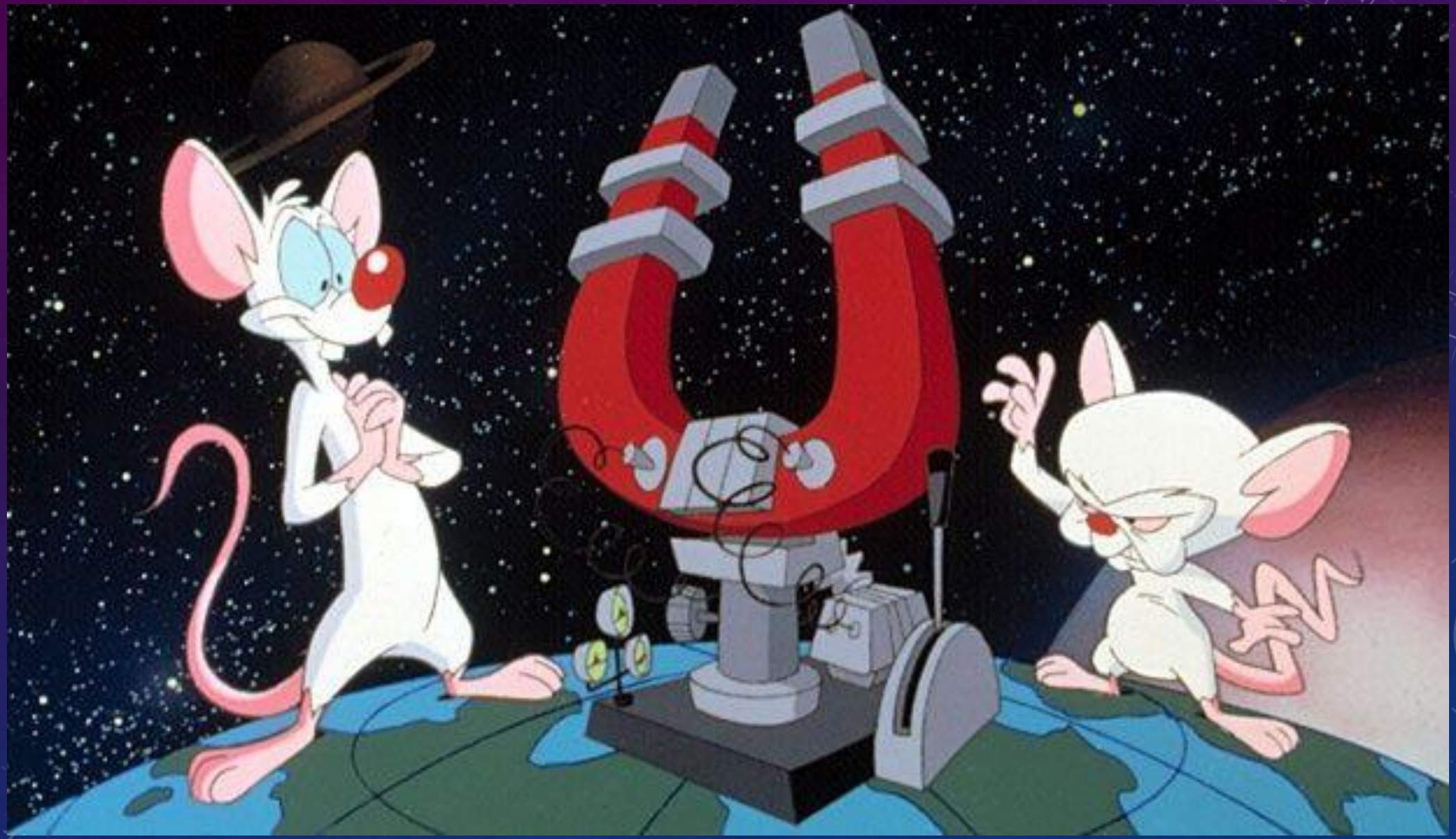




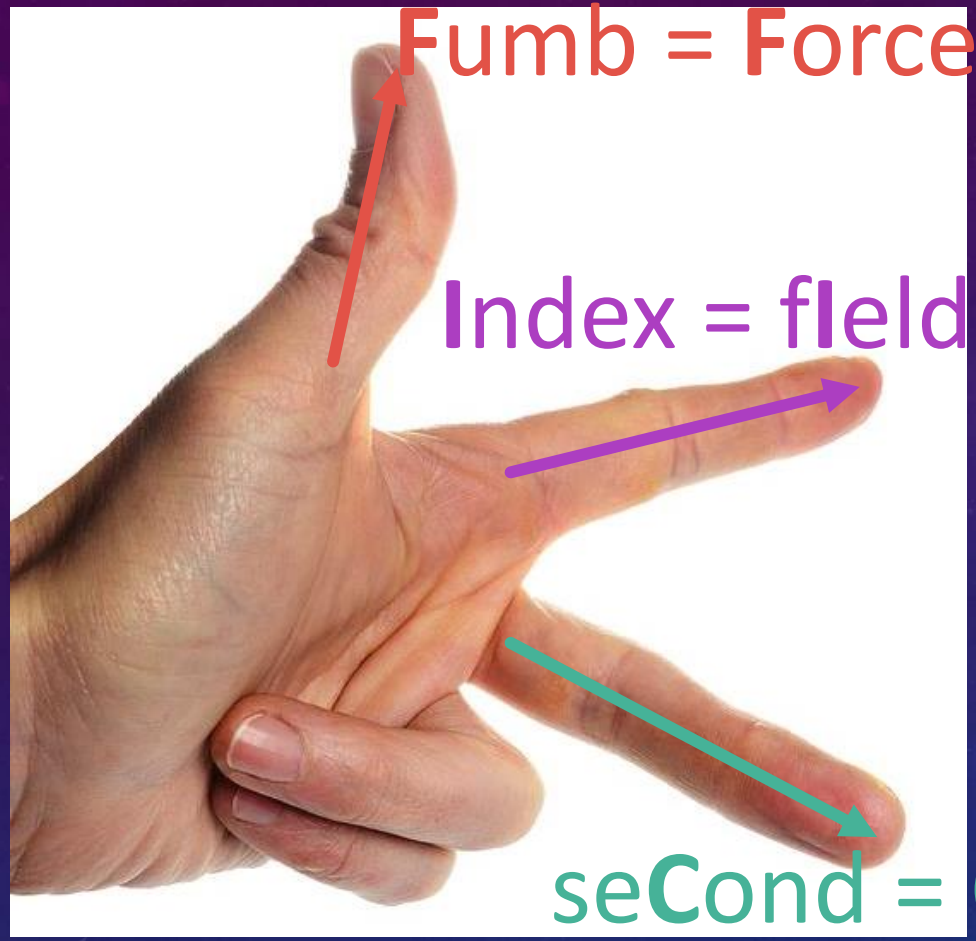
Instead of going in a straight line and using lots of accelerating gaps

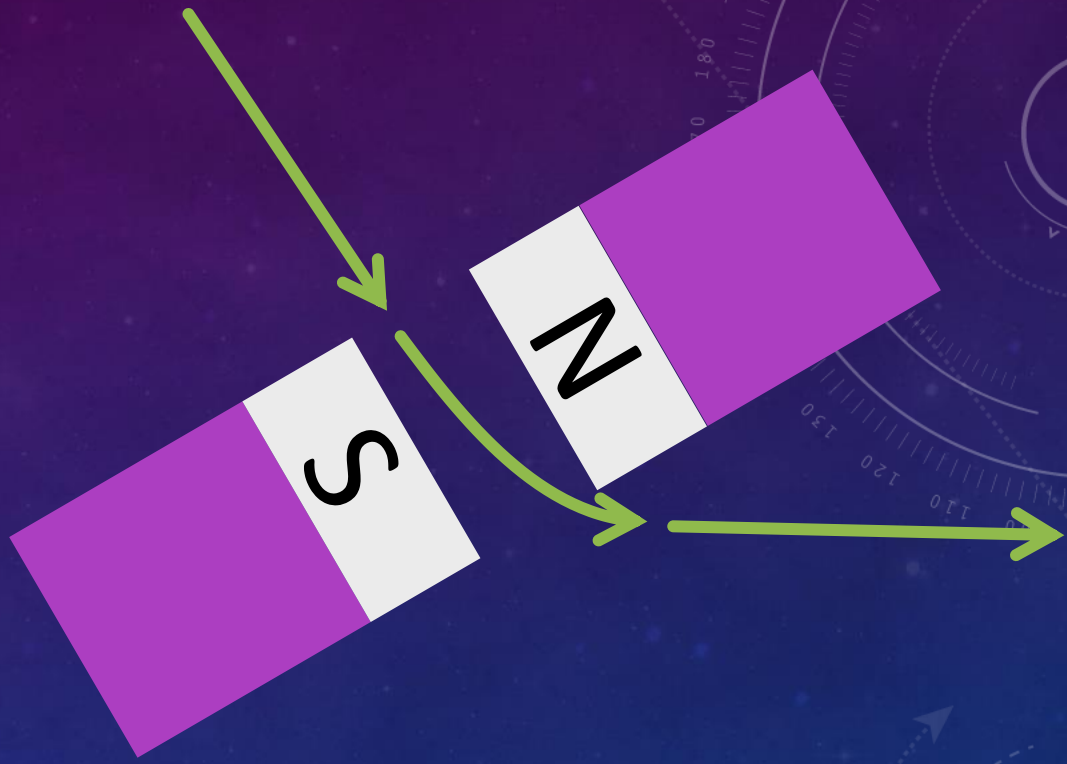


Go in a circle and use the same gap lots of times



BENDING MAGNETS - DIPOLES



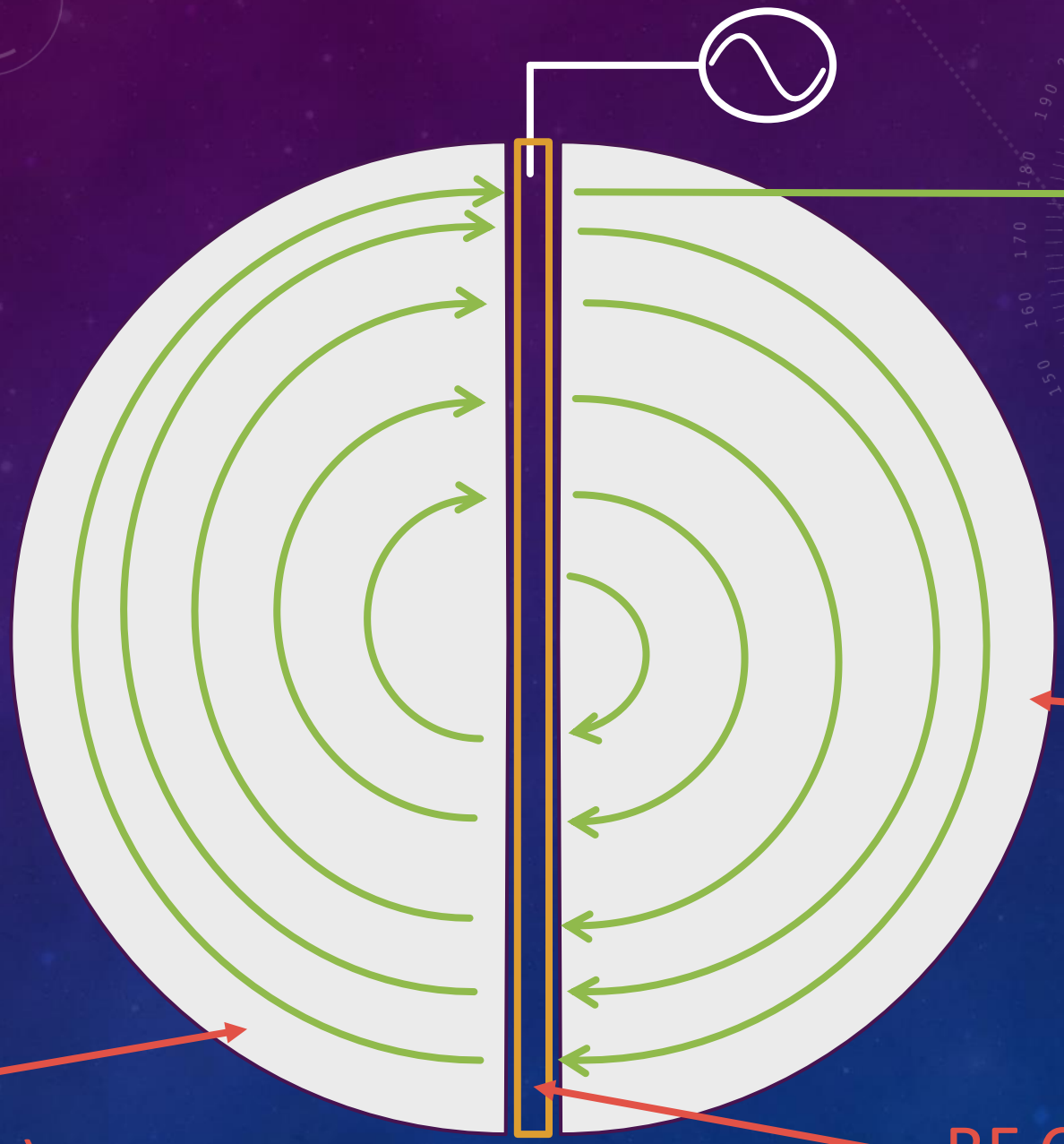


$$\vec{F} = q\vec{v} \times \vec{B}$$

Force applied = Current × Magnetic field

THE CYCLOTRON

- Moving charge follows a curved path in the Dee
- On each crossing of the gap, energy and path radius increase
- Increased path length and increased speed cancel out, fixed time between crossings

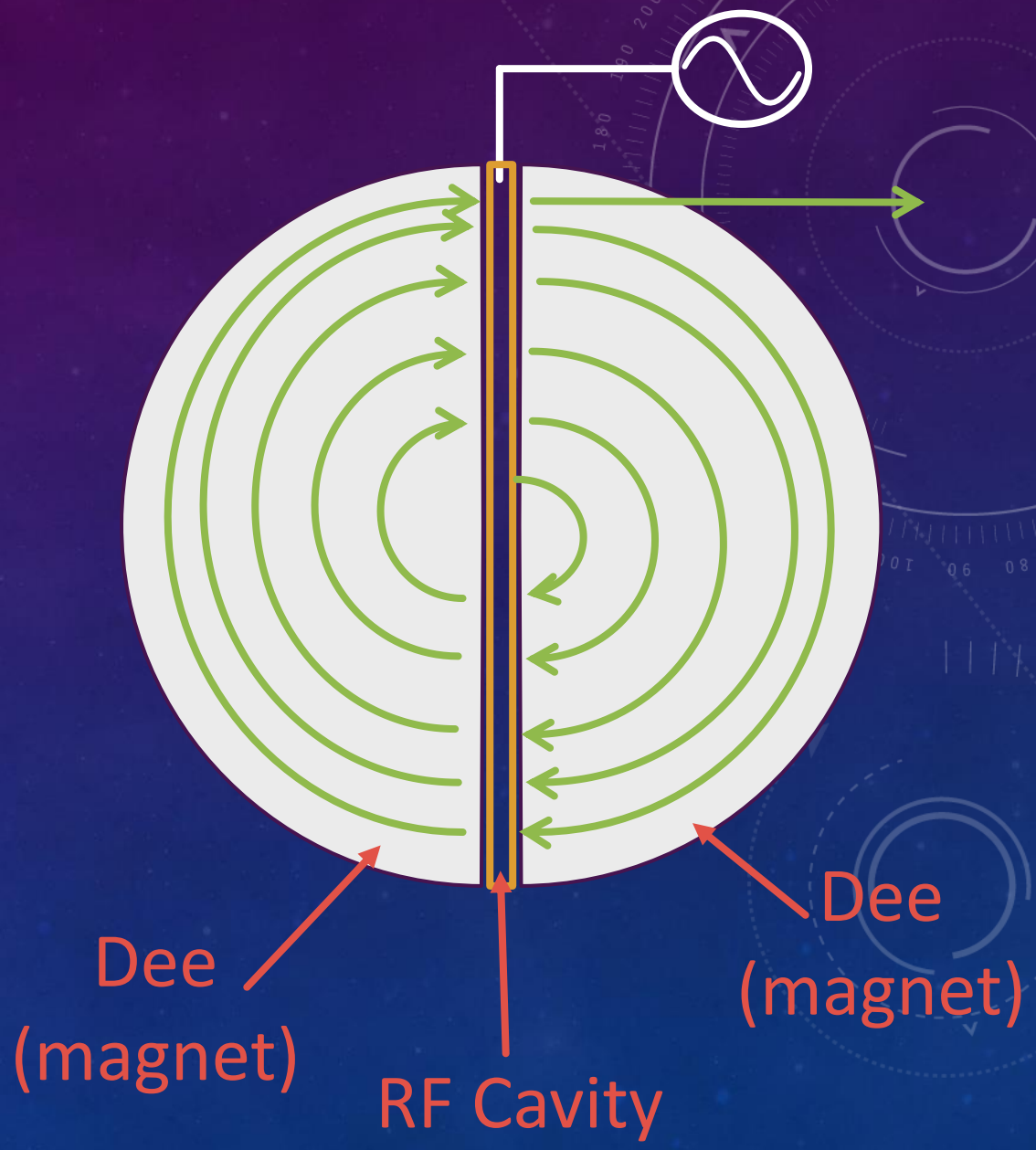


THE CYCLOTRON

$$f_c = \frac{qB}{2\pi m}$$

$$\text{Cyclotron frequency} = \frac{\text{Charge} \times \text{Magnetic field}}{2\pi \times \text{Mass}}$$

- Particle revolution frequency (cyclotron frequency) **independent of radius**
- Excite the RF cavity at f_c (or a multiple)
- Increment the particle energy at each crossing of the cavity

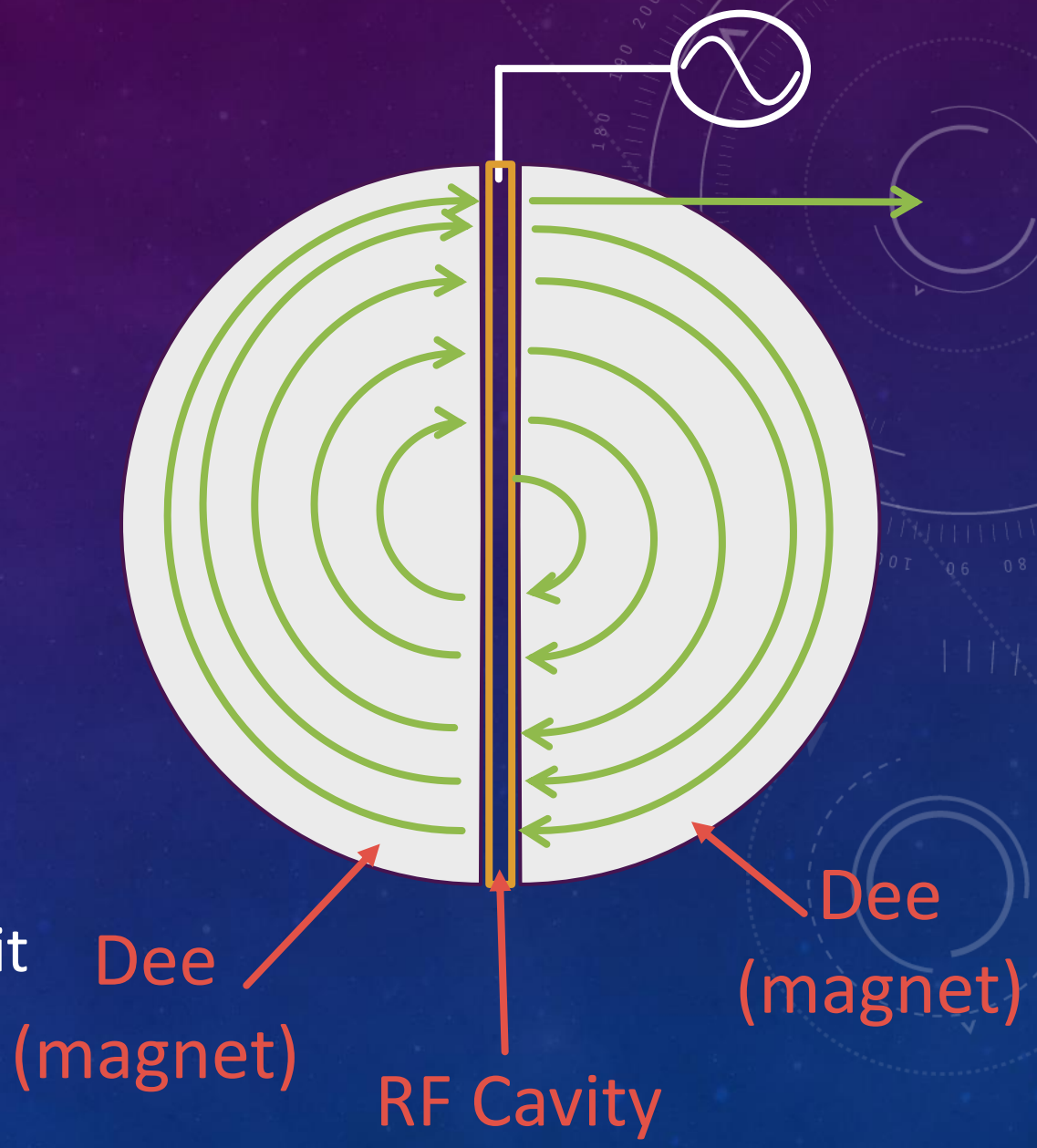


THE CYCLOTRON - LIMITS

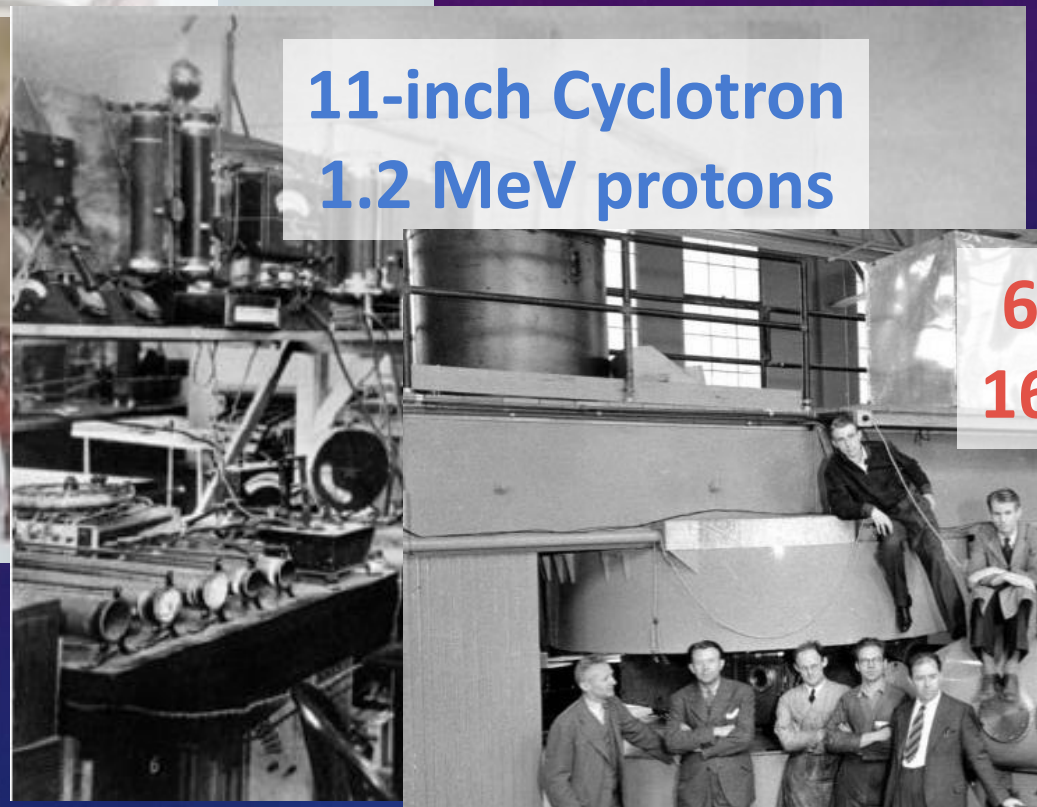
$$f_c = \frac{qB}{2\pi\gamma m}$$

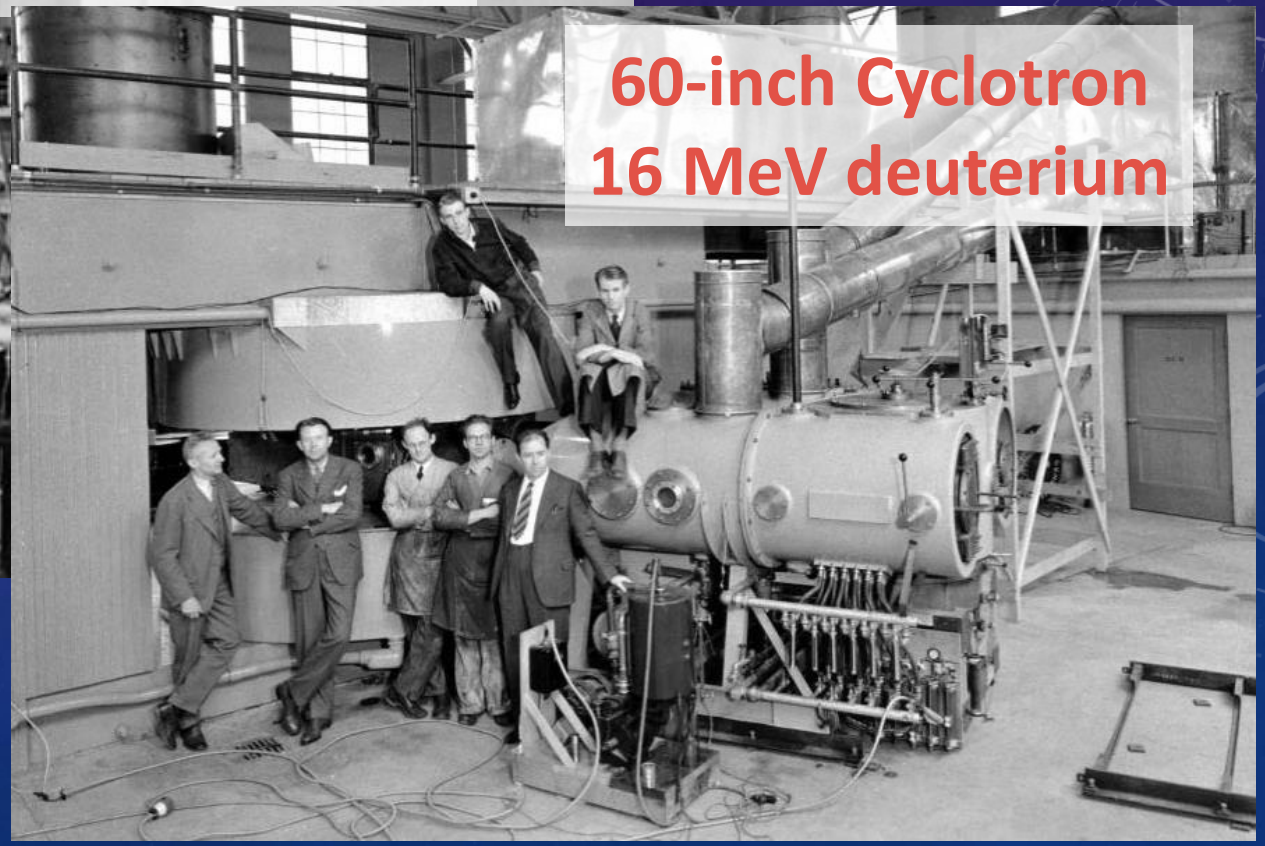
$$\text{Cyclotron frequency} = \frac{\text{Charge} \times \text{Magnetic field}}{2\pi \times \text{Relativistic gamma} \times \text{Mass}}$$

- As the energy increases, relativity starts to matter
- By a few tens of MeV, protons become a bit too relativistic and the frequency drops
- Lose synchronism, acceleration stops

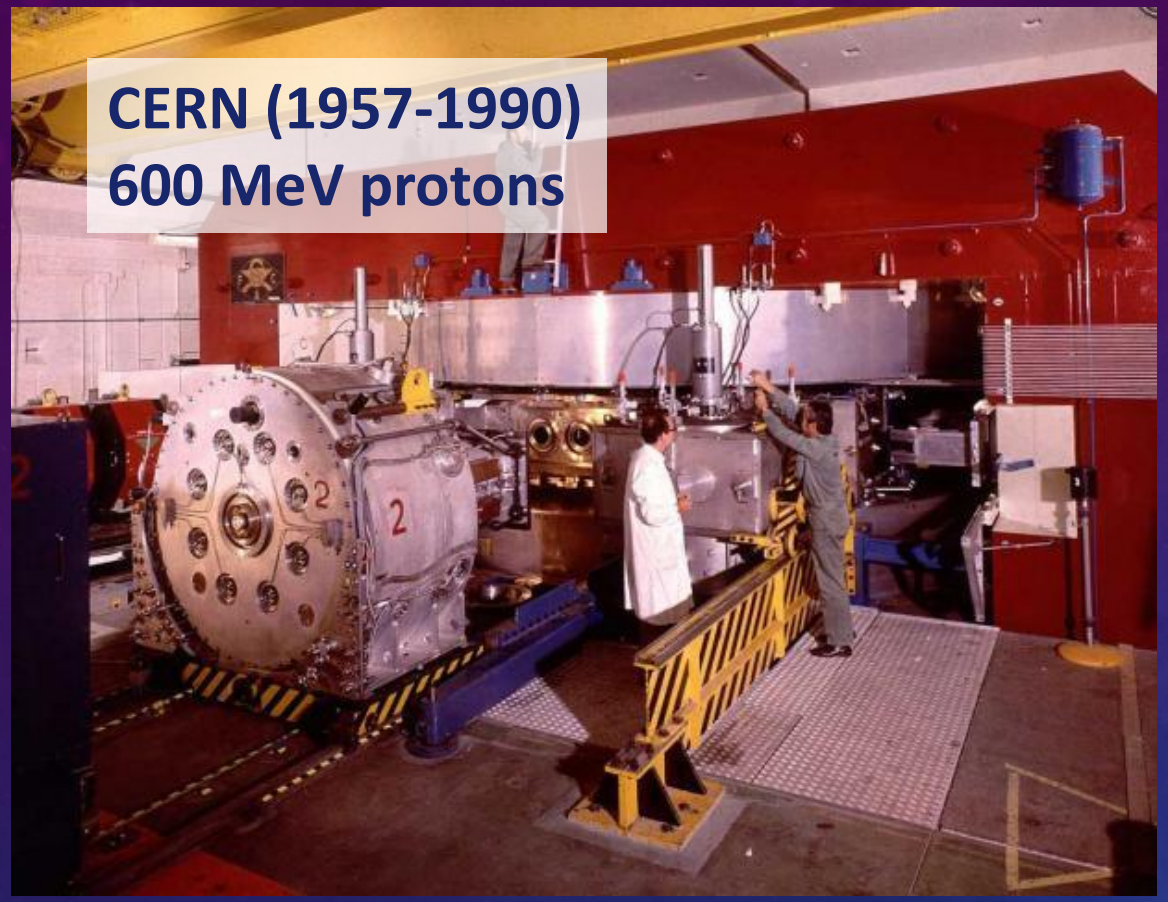


SOME LAWRENCE (ET AL) CYCLOTRONS



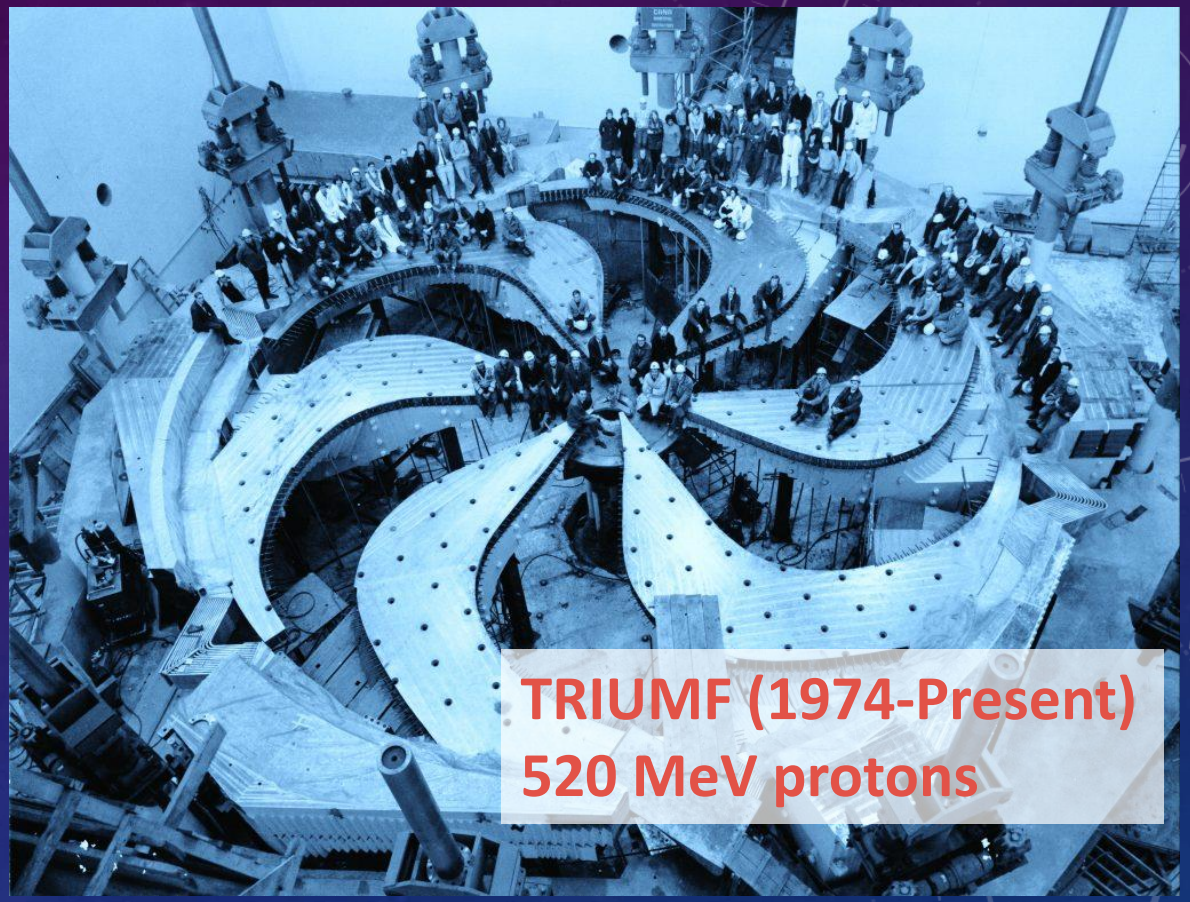


FANCY CYCLOTRONS



Synchrocyclotrons:

- Adapt the RF frequency to compensate for relativistic effects



Sector cyclotrons:

- Non-uniform magnetic field reshapes the orbit to maintain frequency for longer

I WANT MOAR!
MOOOAAARRR!!!

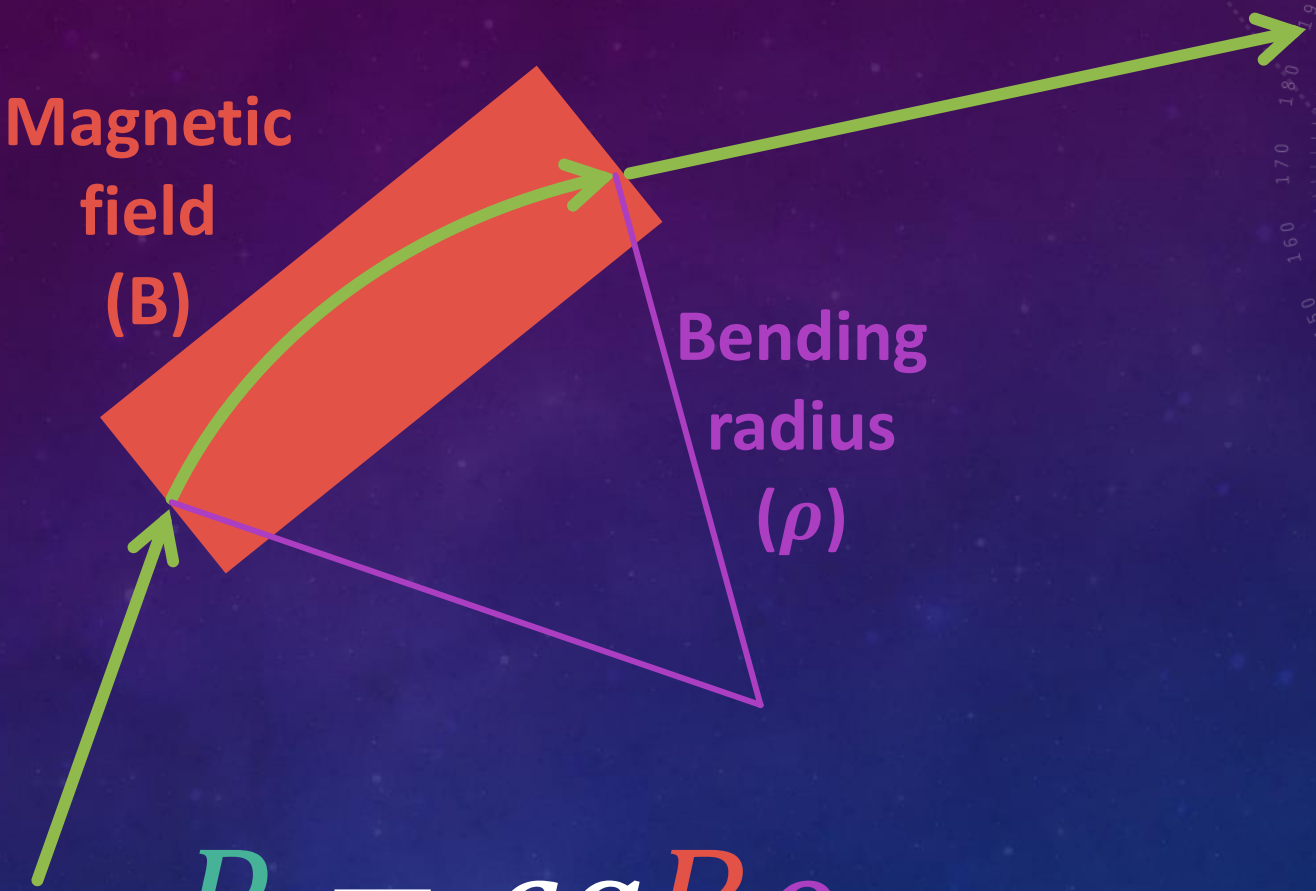
BEYOND THE CYCLOTRON

- Classical cyclotrons are limited to around 20 MeV
- With further developments, energies pushing 1 GeV can be reached
- Need an accelerator that can operate through to the ultra-relativistic regime

Synchrotrons:

- Constant orbital radius
- Magnetic field varies with time
- RF frequency changes synchronously with the magnetic field

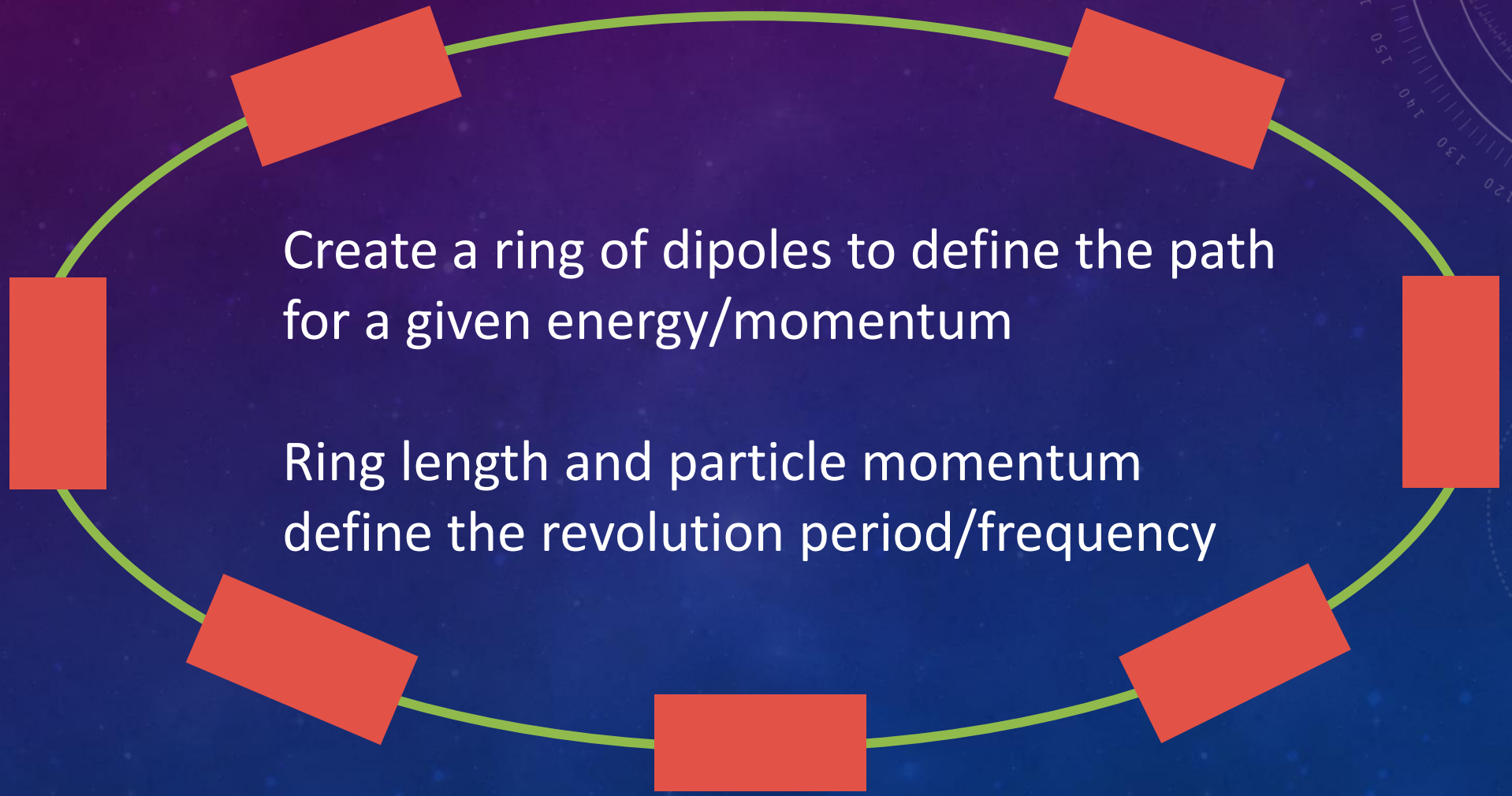
DIPOLE MAGNETIC FIELD AND MOMENTUM



$$P = cqB\rho$$

Momentum = Speed of light × Charge × Magnetic field × Bending radius

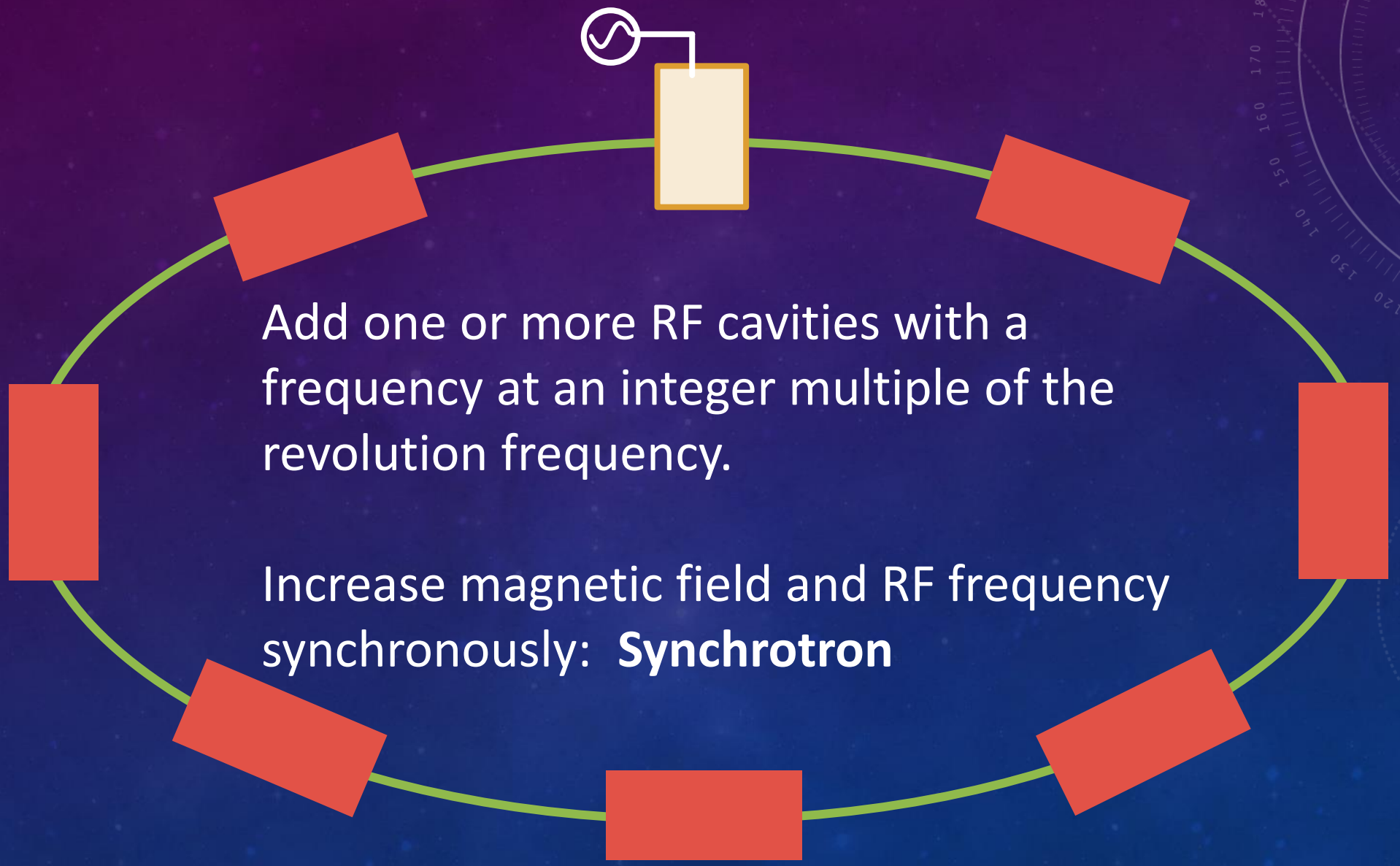
CREATE A SYNCHROTRON



Create a ring of dipoles to define the path for a given energy/momentum

Ring length and particle momentum define the revolution period/frequency

CREATE A SYNCHROTRON

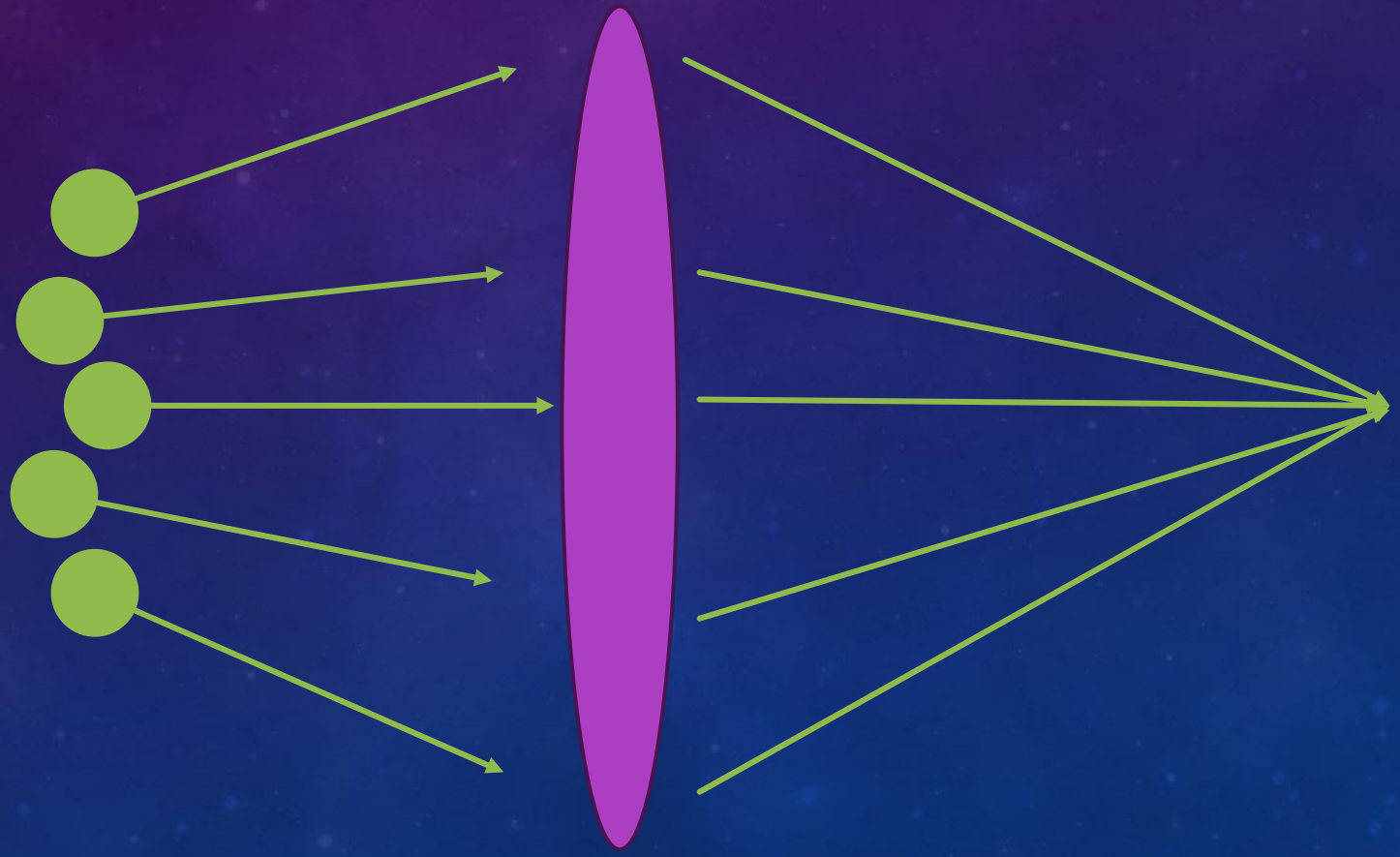


Add one or more RF cavities with a frequency at an integer multiple of the revolution frequency.

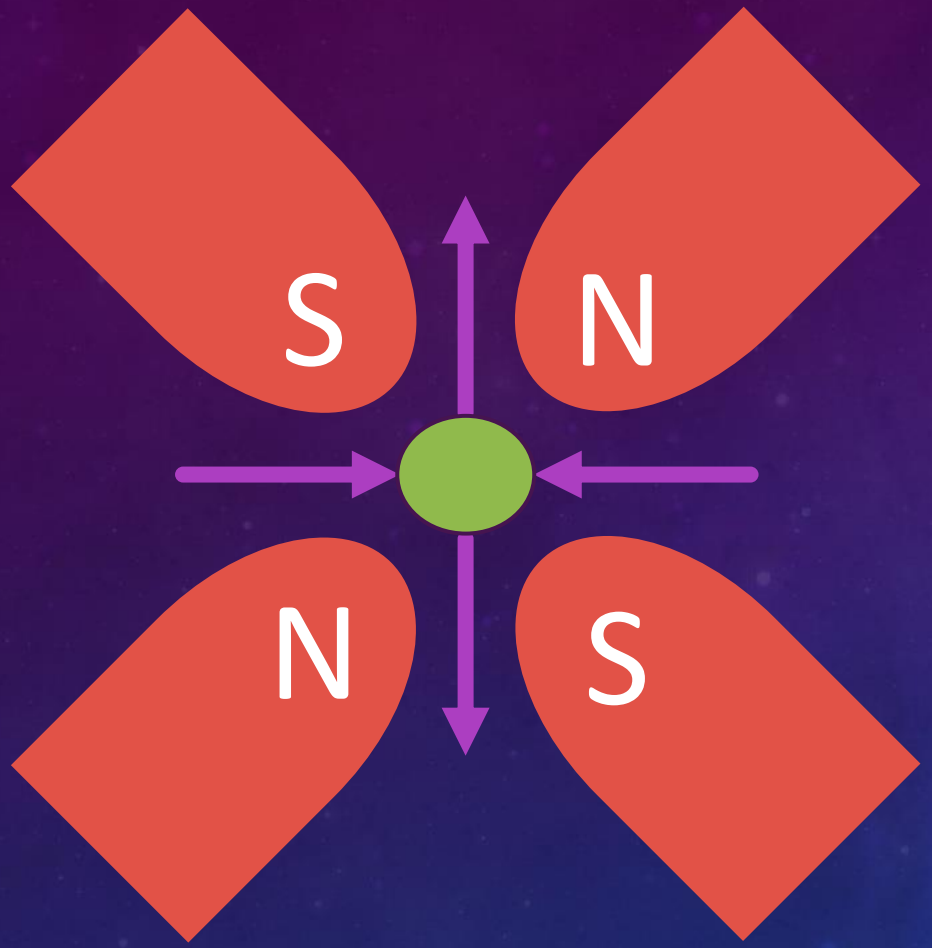
Increase magnetic field and RF frequency synchronously: **Synchrotron**

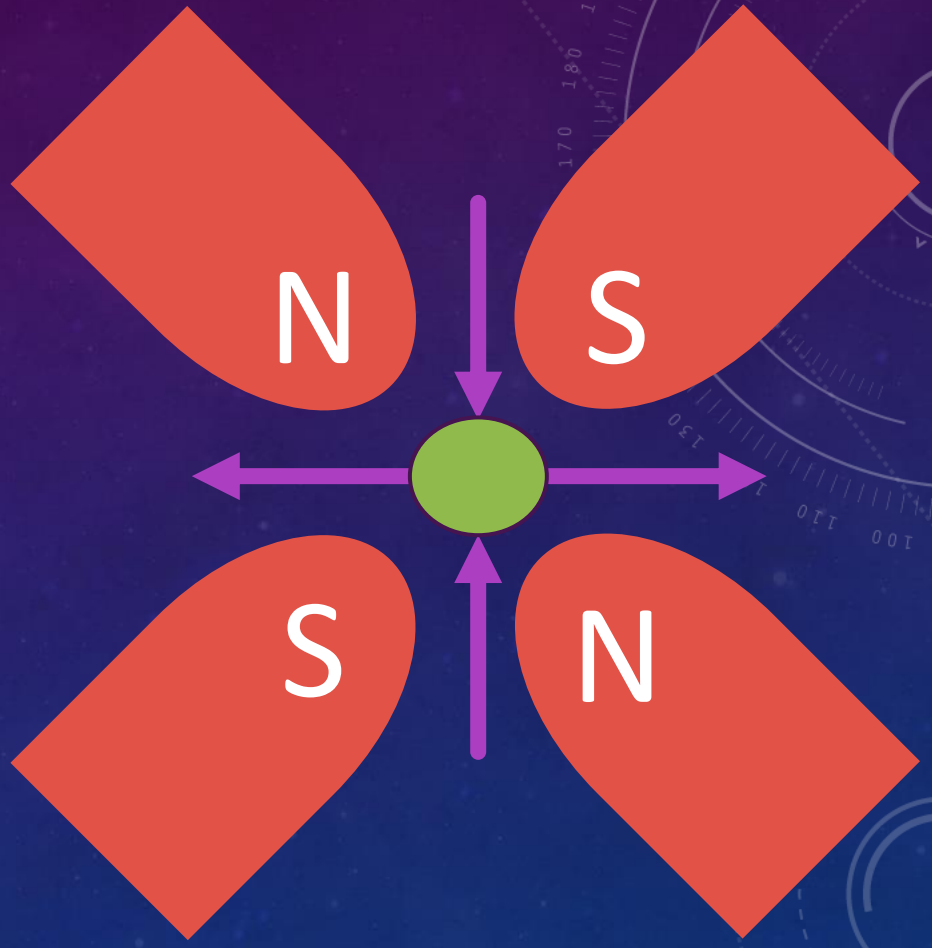
FOCUSING

- Particle beams are never perfectly laminar
- Like-charges repel each other
- Lenses are used to focus the beam



FOCUSING MAGNETS - QUADRUPOLES





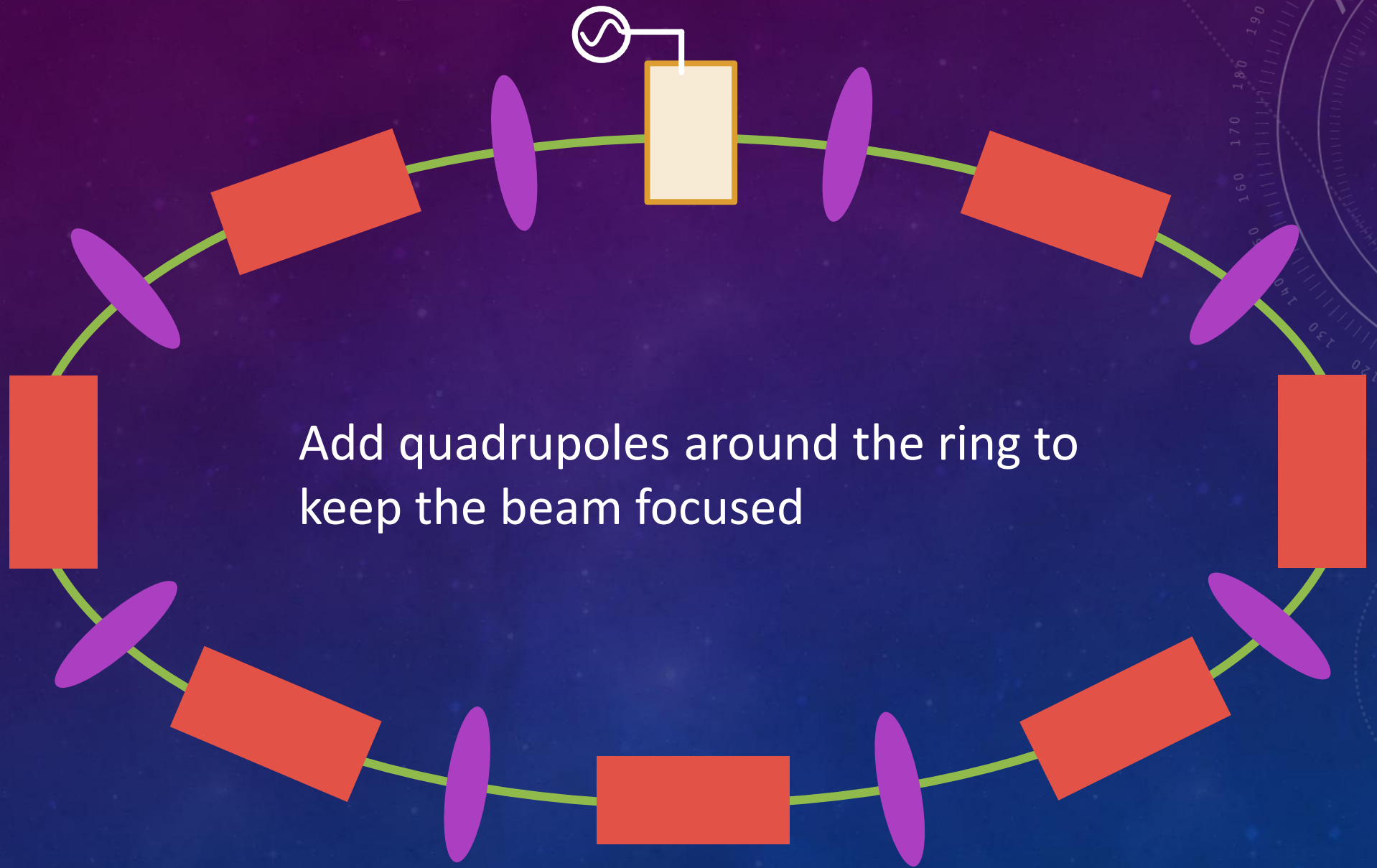
Focusing quadrupole:

- Focuses in the horizontal plane
- Defocuses in the vertical plane

Defocusing quadrupole:

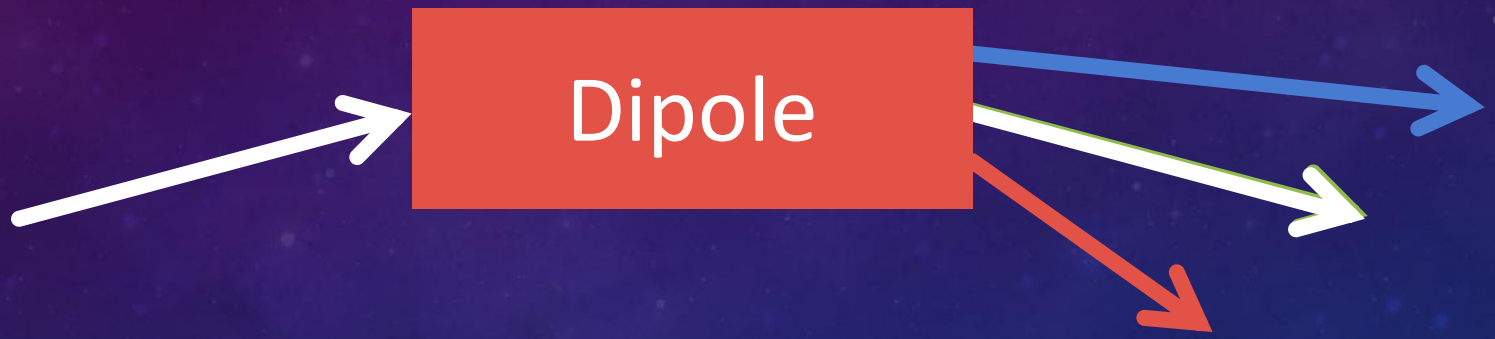
- Defocuses in the horizontal plane
- Focuses in the vertical plane

FOCUSING CHANNEL



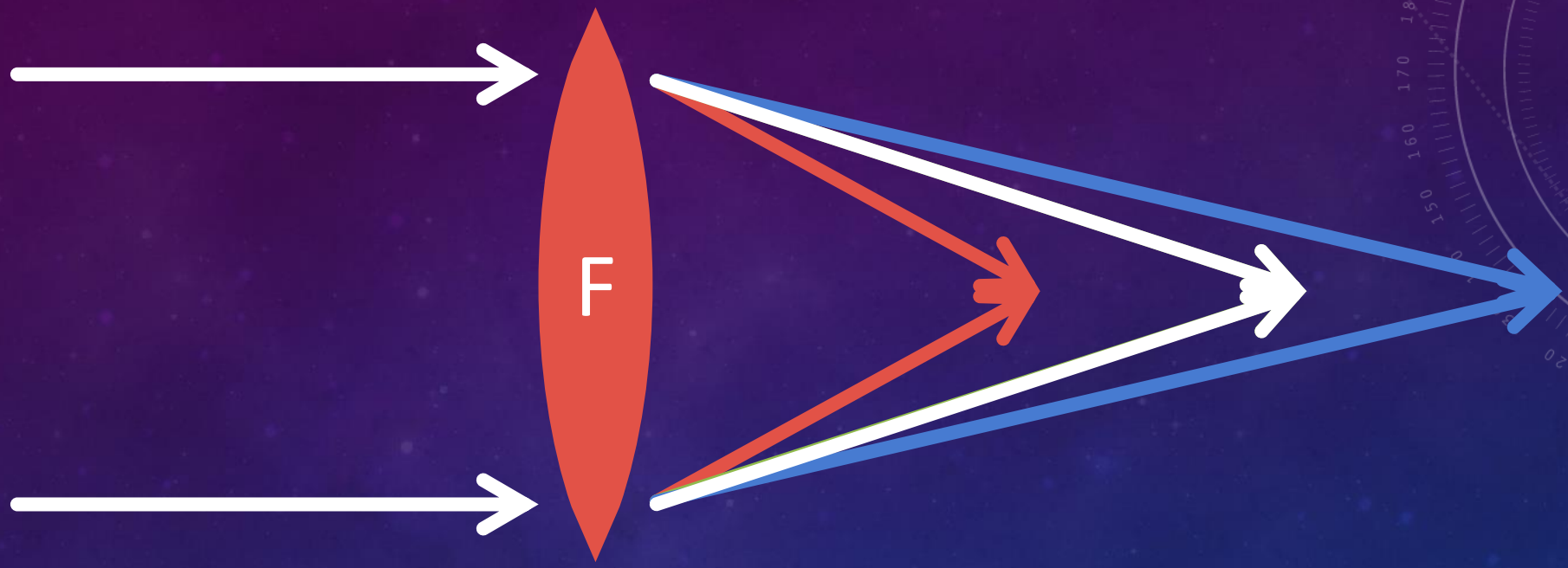
Add quadrupoles around the ring to keep the beam focused

DISPERSION



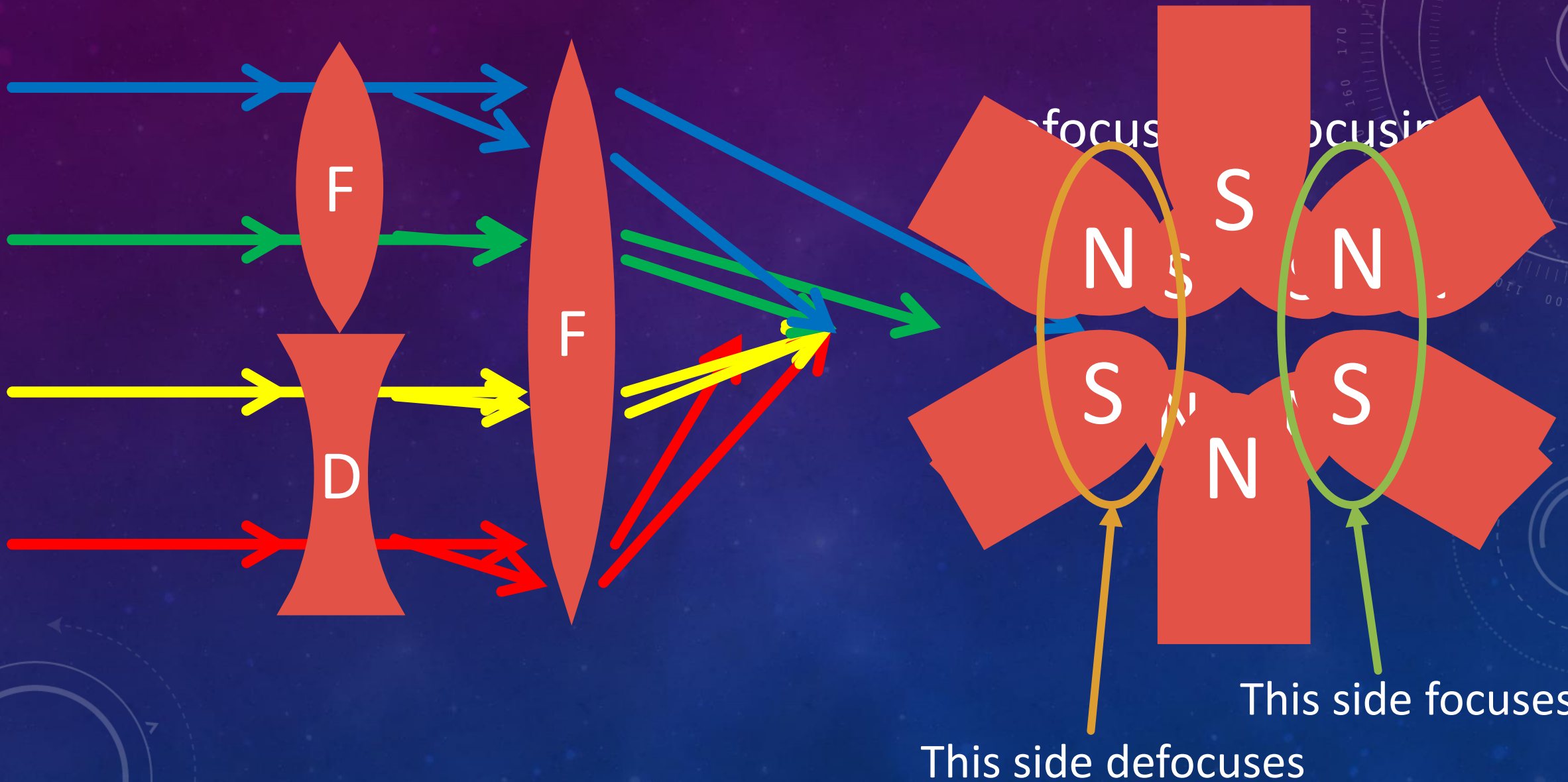
- The particles have a range of energies (momenta)
- For a given magnetic field, high momentum particles bend less than low momentum particles, causing the beam to spread out

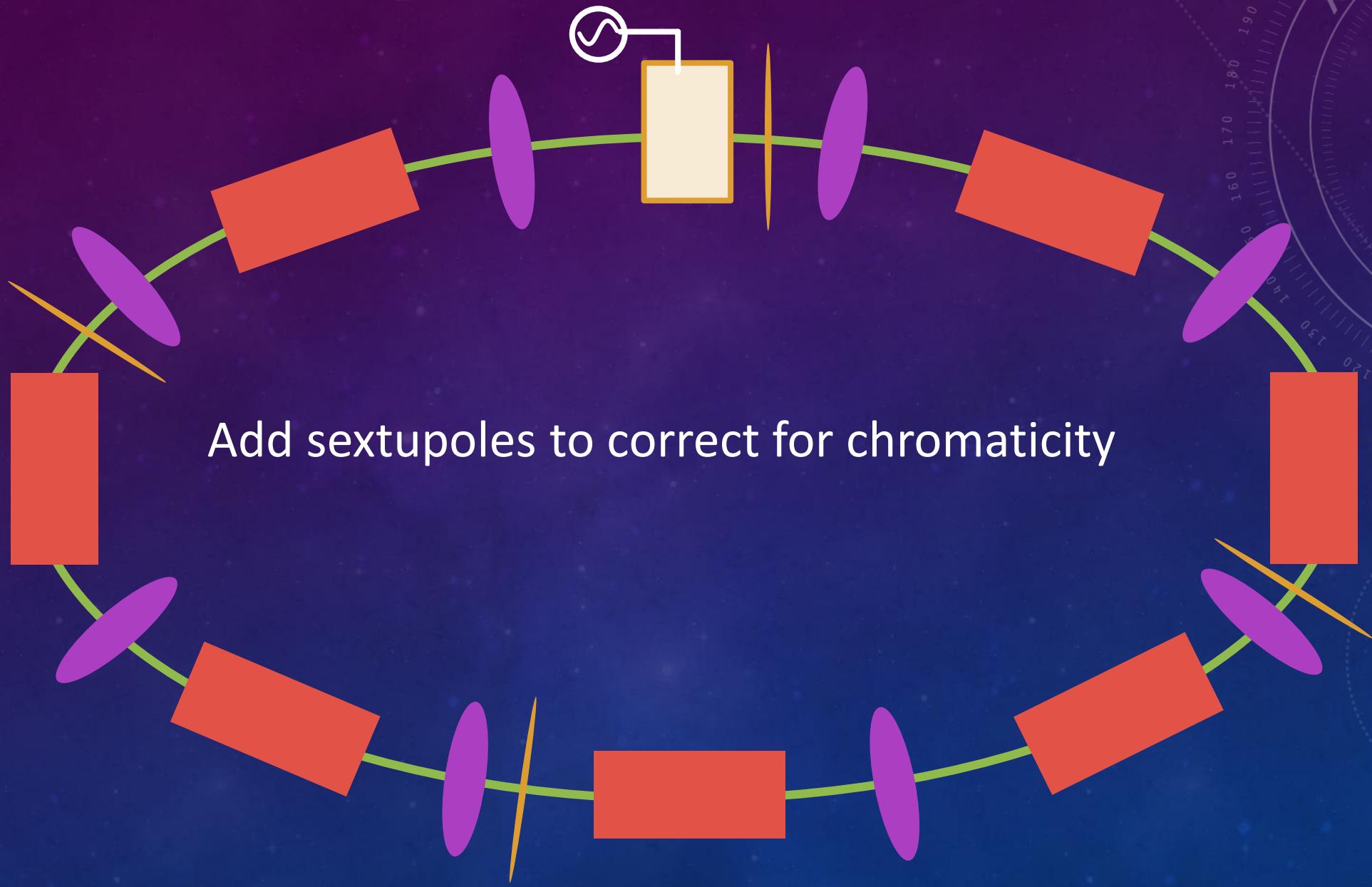
CHROMATICITY



- High energy particles are focused less
- Low energy particles are focused more
- For correct focusing, another magnet is added

CHROMATICITY CORRECTION - SEXTUPOLE



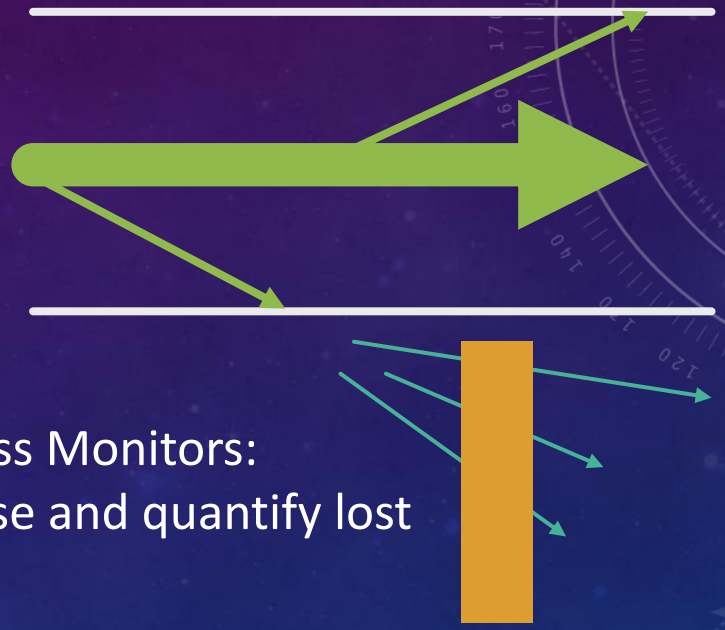


Add sextupoles to correct for chromaticity

BEAM INSTRUMENTATION

Beam Position Monitors:

- Measure the beam's horizontal/vertical offset

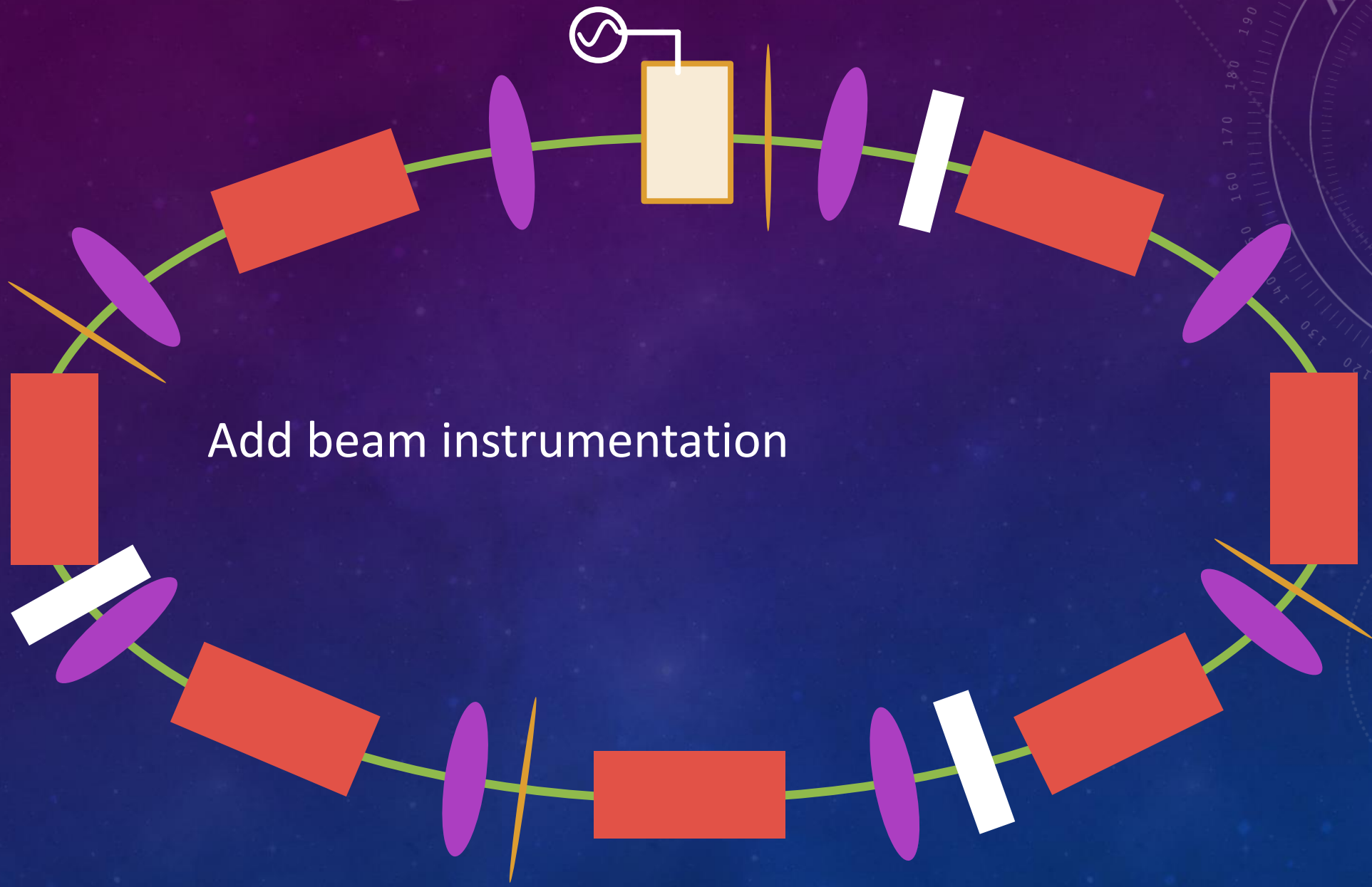


Beam Loss Monitors:

- Localise and quantify lost beam

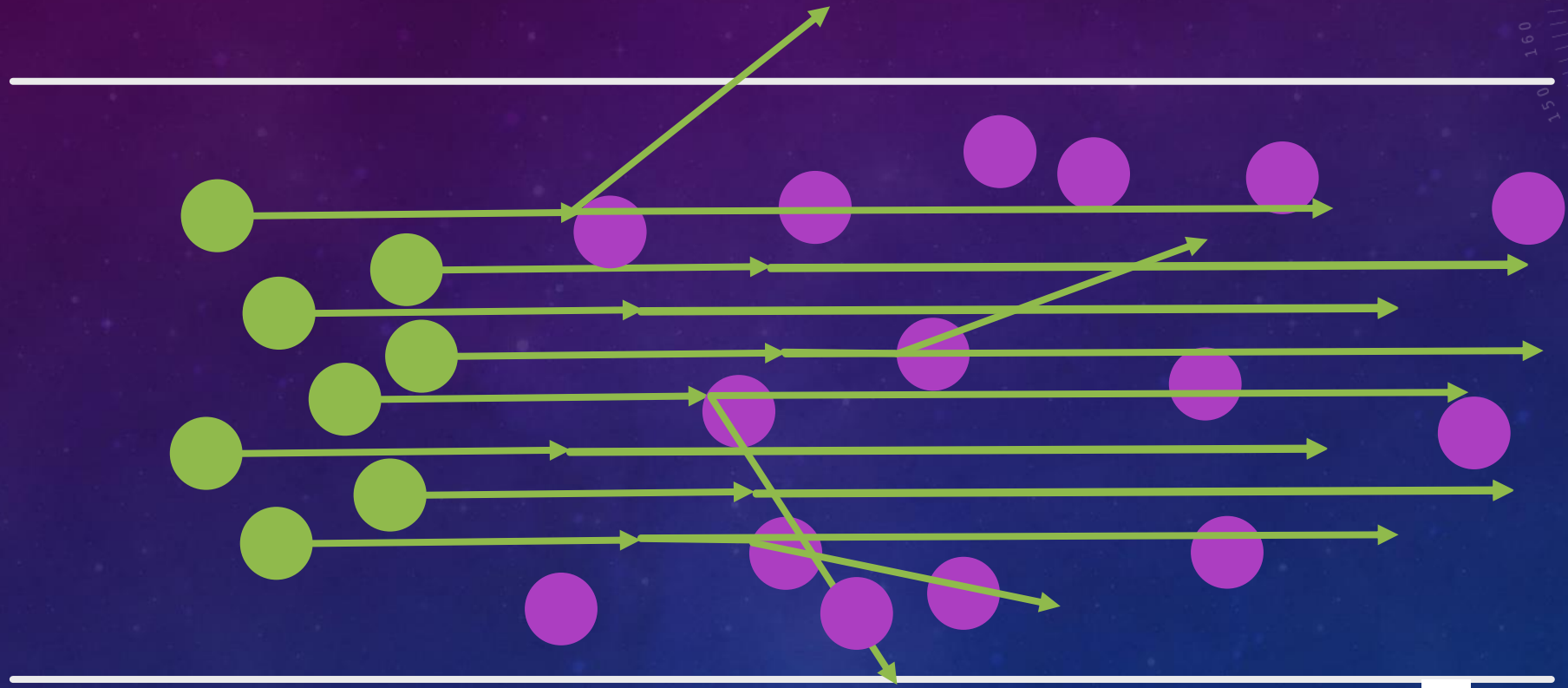
Beam profile measurement

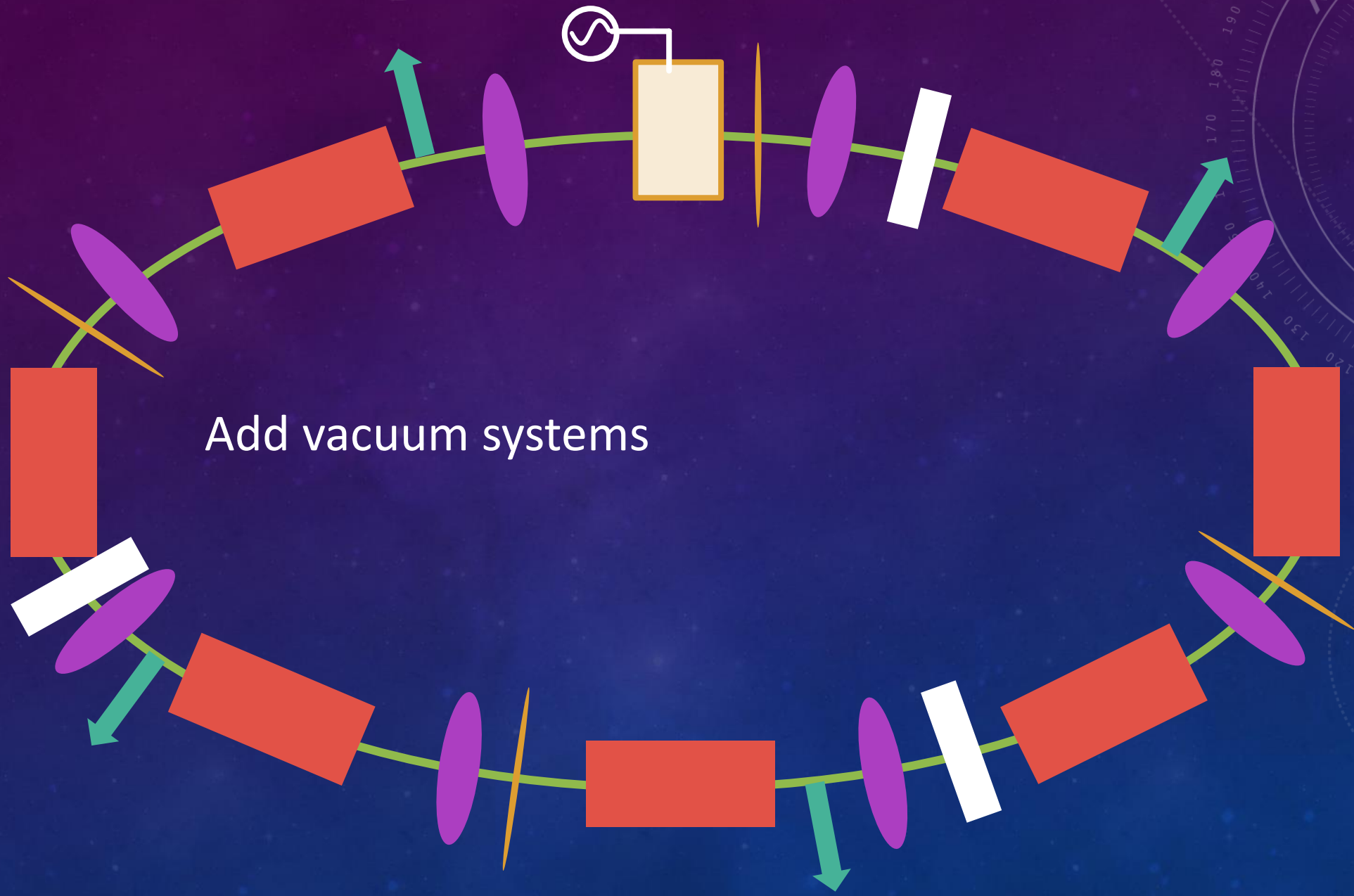
- Measure the beam distribution in 3D



Add beam instrumentation

VACUUM



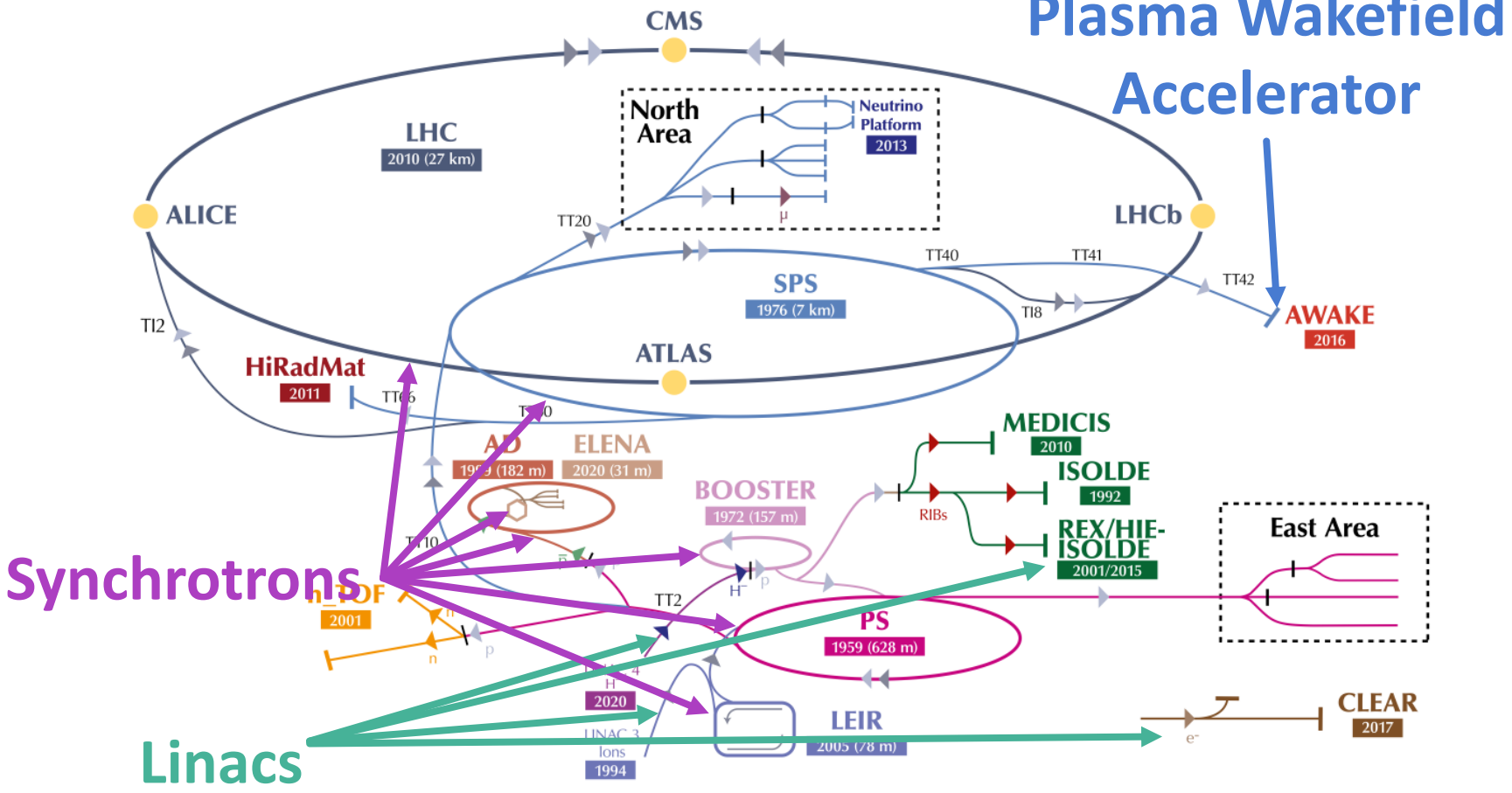


Add vacuum systems

ANYTHING ELSE?

- Injection and extraction systems
  - Fast pulsing magnets to get beam in and out of the accelerator
- Collimators
  - Absorb lost beam in a controlled way at predefined locations
- Higher order magnets
  - Correct additional errors and influence more beam parameters
- Additional RF systems
  - Manipulate the longitudinal beam parameters
- Feedbacks
  - Identify and correct errors that might degrade the beam
- …..

The CERN accelerator complex
Complexe des accélérateurs du CERN



▶ H⁻ (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ p̄ (antiprotons) ▶ e⁻ (electrons) ▶ μ (muons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

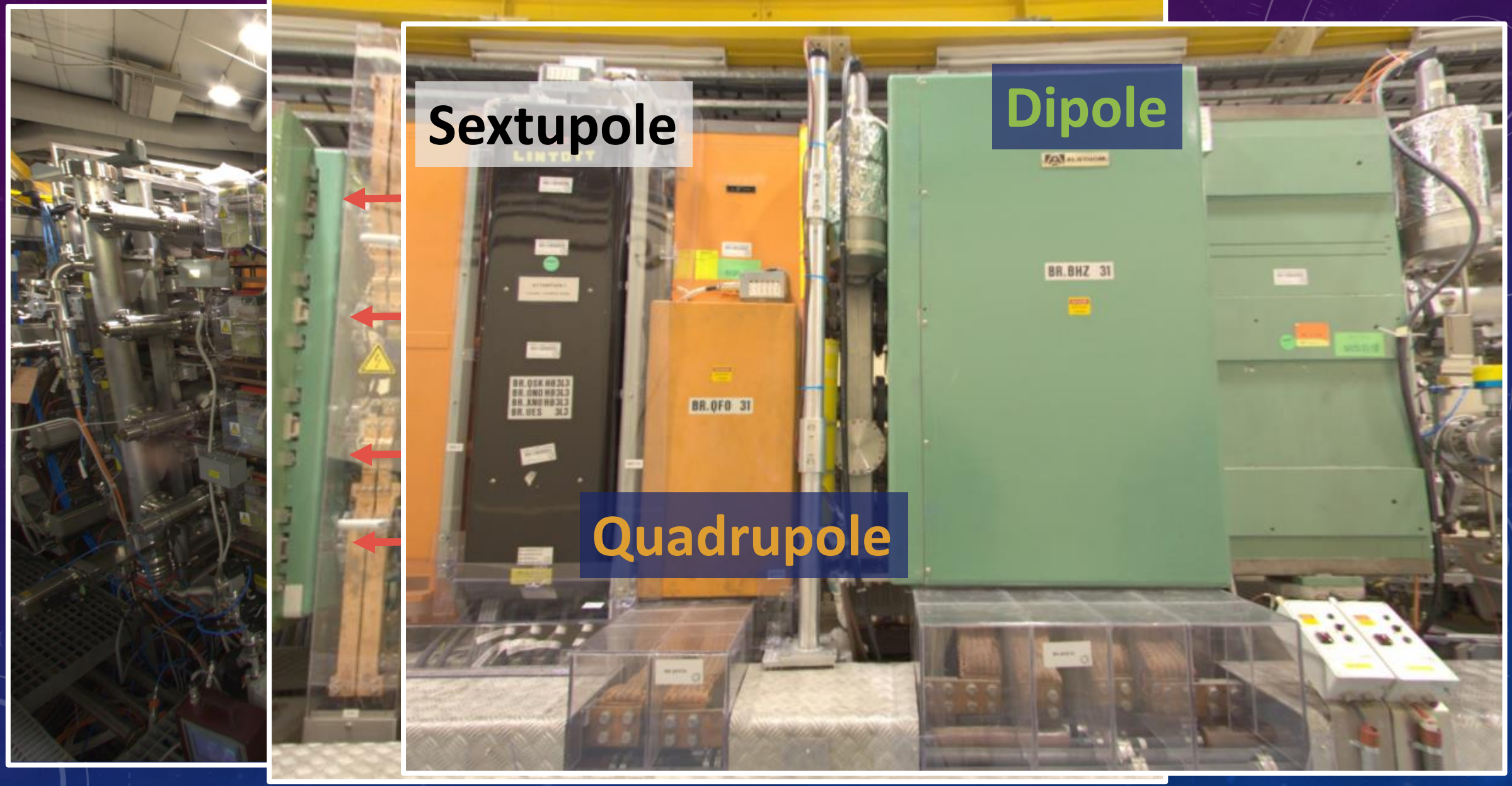
LINAC4

High voltage platform:
- H^- ion source
- Electrostatic acceleration

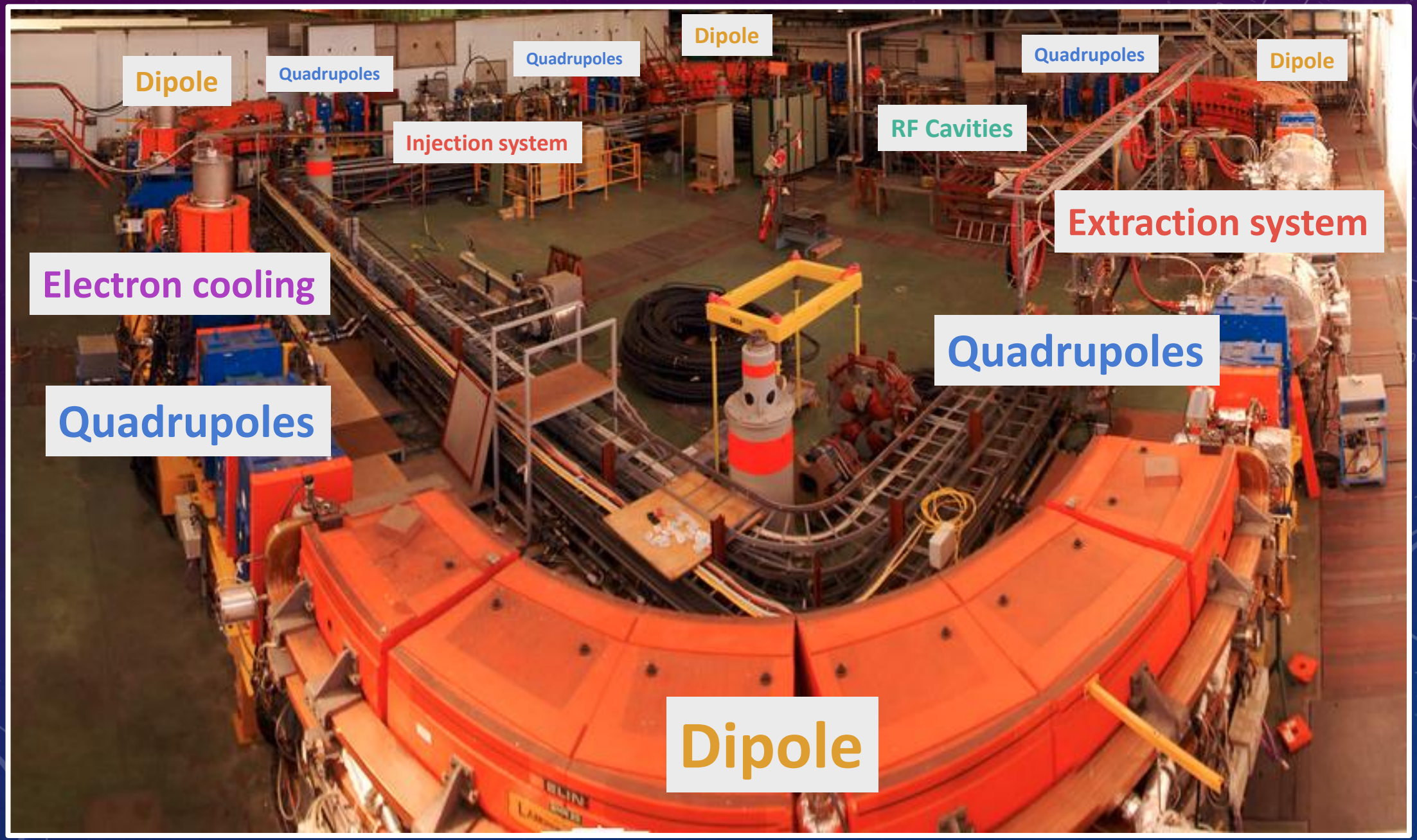
Radiofrequency Quadrup
- Structure that both ac
and focuses at the sa

Drift Tube Linac (DTL)

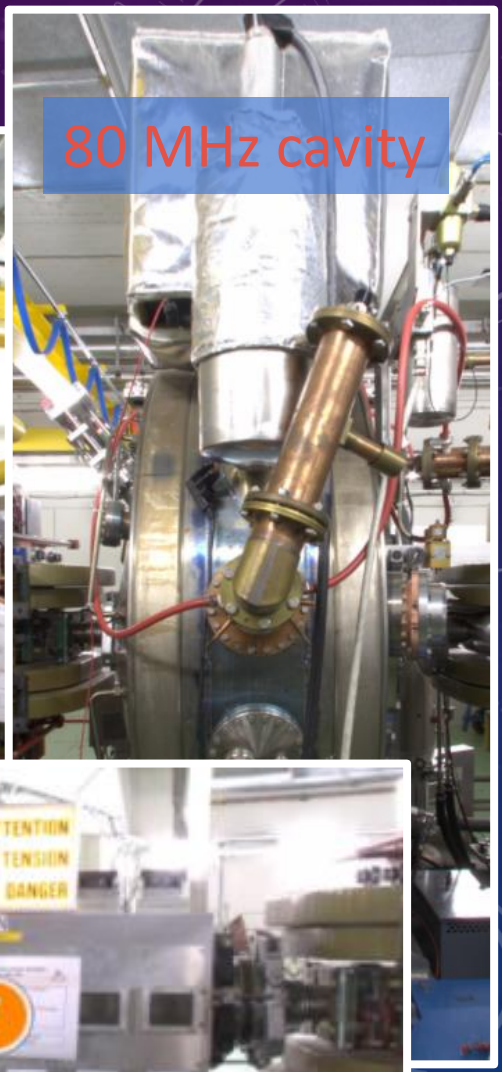
PS BOOSTER



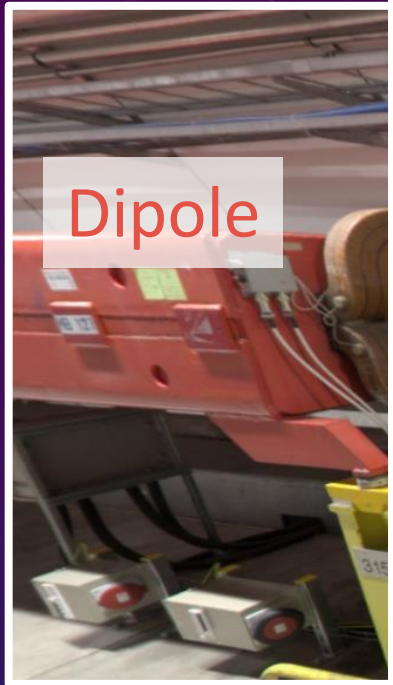
LOW ENERGY ION RING

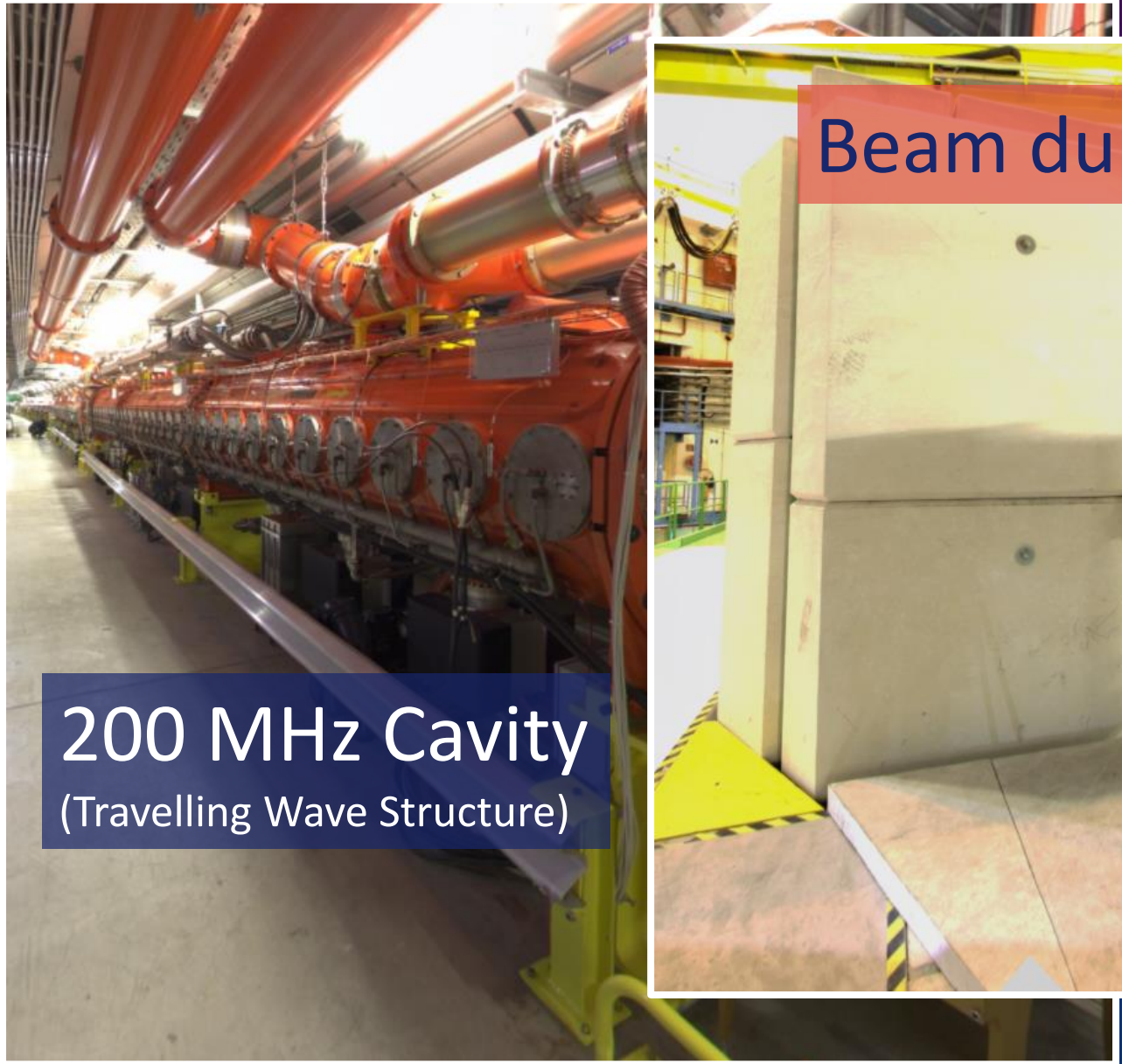


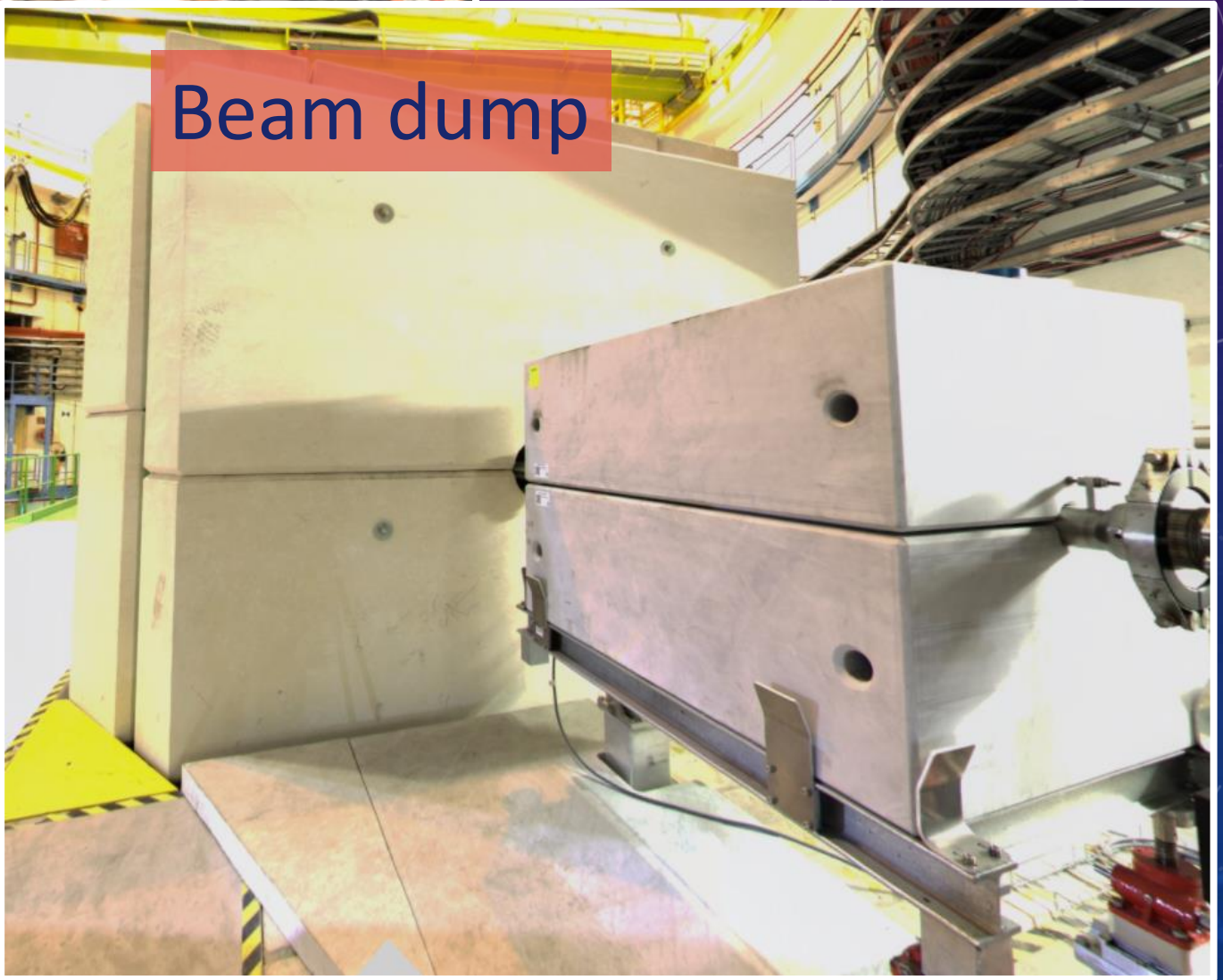
PROTON SYNCHROTRON



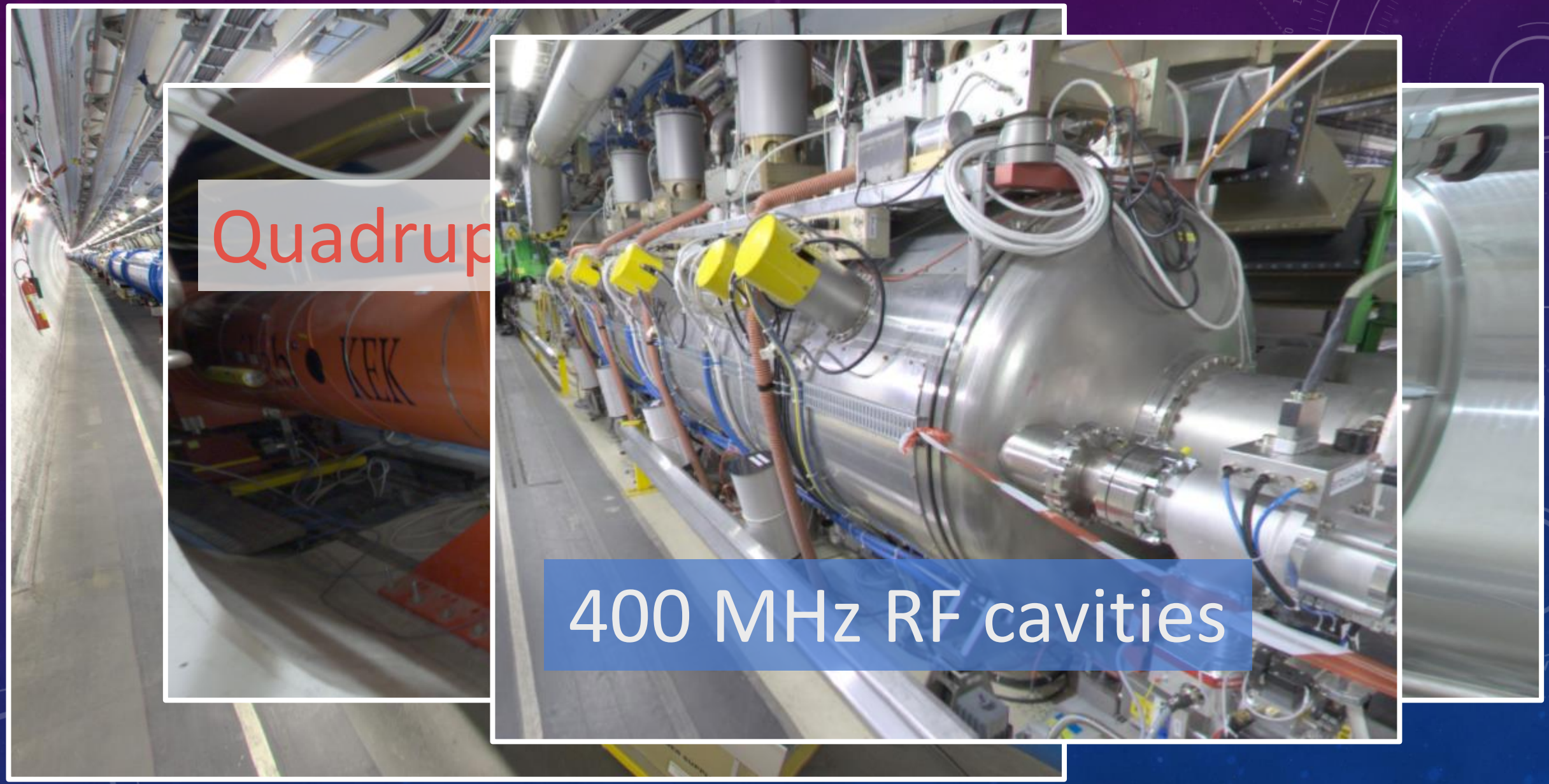
SUPER PROTON SYNCHROTRON





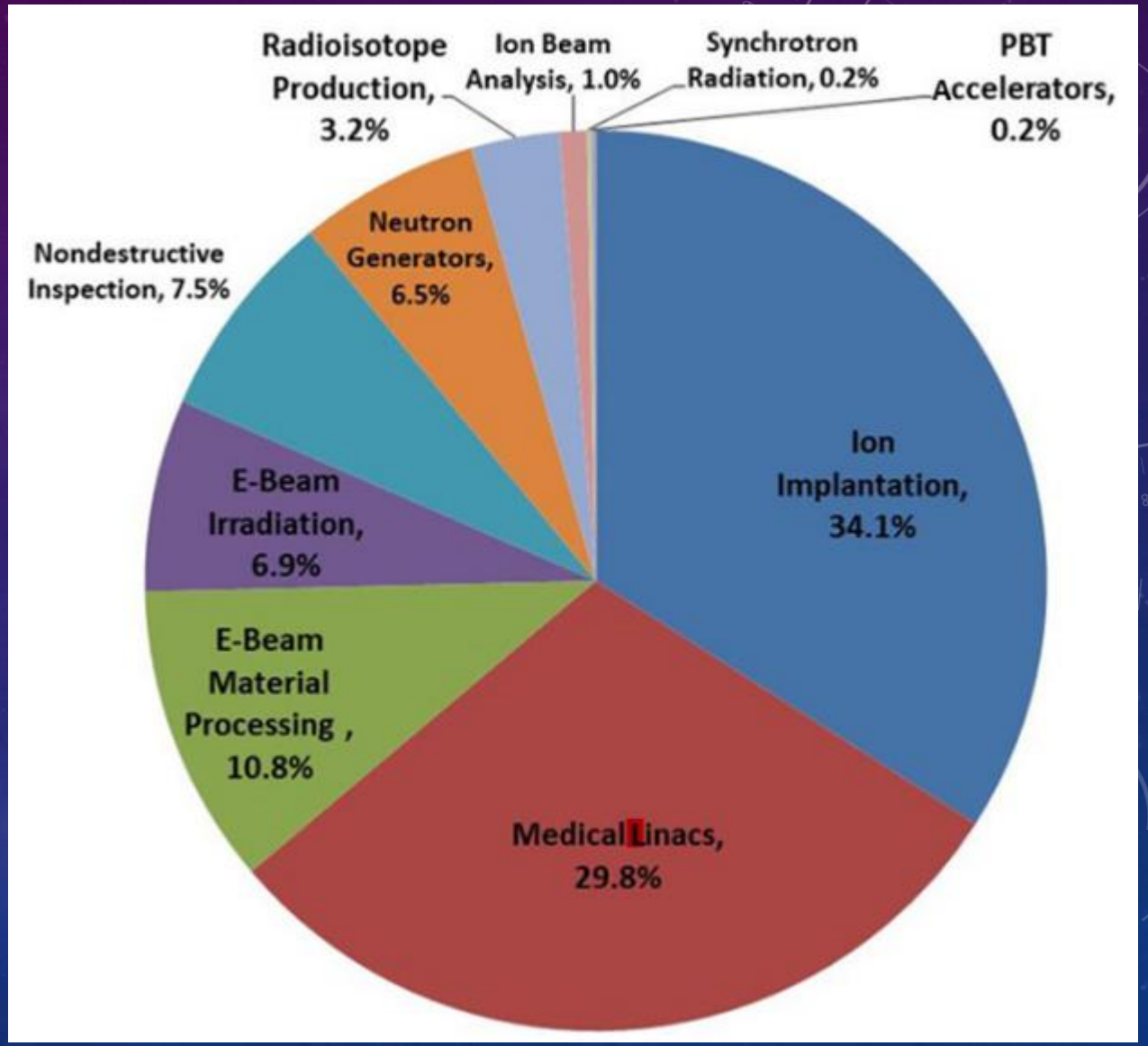


LARGE HADRON COLLIDER



INDUSTRIAL APPLICATIONS

- Many thousands of accelerators in the world
- The vast majority are used in industry and medicine
- The underlying physics and engineering requirements are universal, the rest is a matter of context



The future of Industrial Accelerators and Applications, B. Doyle et al, Reviews of Accelerator Science and Technology Vol. 10 (2019)

	Linear	Circular	
DC	• Very flexible (no need for synchronism) • Energy limited by electric field strength		
AC	• Cavity design depends on β, varies along the linac • Increasing energy requires more RF cavities • Very fast acceleration	**Cyclotron** • Fixed frequency and field (usually) • Large magnets and vacuum vessels • Energy limited by relativity and size	**Synchrotron** • Magnetic field and RF frequency ramp synchronously • Energy limited by magnet strength and ring size

OTHER TYPES OF ACCELERATOR

- Betatron: Magnetic field for steering and accelerating
- Plasma wakefield: Particles accelerated in bubbles of plasma
- Induction: Magnetic induction accelerates the beam
- Laser radiation pressure: High powered laser pushes particles
- Fixed field accelerator: Best bits of cyclotrons and synchrotrons
- …

SUMMARY

- Particle accelerators can be small (fit in a microwave), very **very** large (27 km) and anything in between
- Electric fields add energy to the beam, magnetic fields steer and focus the beam (with exceptions)
- Electrostatic accelerators can accelerate “anything” but are limited to a few MV, typically 10s-100s kV
- Radiofrequency cavities allow many sequential energy increments in linear or circular accelerators
- Only a small fraction of accelerators are used for fundamental research, most are tools for industry and medicine